The Dual-Readout Technique for ORKA Experiment at Fermilab

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Rationale

- The Dual-Readout is a calorimetric technique based on the simultaneous measurement of two different signals from the same shower and reflecting two different physics mechanisms.

- This technique has been proposed to eliminate the factors that limit the performance of hadron calorimeters such as electromagnetic fraction fluctuations in the shower development.

- By comparing signals generated by the Cerenkov and the scintillation lights, it is possible to determine the electromagnetic shower fraction on an event-by-event base.

- Initially proposed by DREAM Collaboration, this technique has been successfully dimonstrated to improve the hadronic energy resolution of a fiber Dual-Readout calorimeter.

- Realistic layout of a fiber Dual-Readout calorimeter has been proposed by the 4th Concept Collaboration at ILC and an intensive simulation program has culminated with the submission of the LoI on March 31, 2009.

Rationale (con't)

- A new detection technique, ADRIANO, has been proposed to overcome the low photo-electron statistics in the Čerenkov signal and sampling fluctuations of the above sampling Dual-Readout calorimeters.

- An extension of ADRIANO technique has been proposed for the ORKA experiment at Fermilab.

- Exploiting ADRIANO potentialities, the goal is to achieve superb detection efficiency, while reducing accidentals which can be detrimental to the ORKA sensitivity goal.

- ADRIANO technique has been the subject of an intense simulation program that has culminating in an equally intense ongoing R&D program.

Outline

- **Dual-Readout technique**

High Energy Resolution Calorimeter for Lepton Collider.

Dual-Readout ADRIANO calorimeter simulation.

ADRIANO and prototype R&D.

- **ORKA Experiment at Fermilab**

Goals and issue

ADRIANO for ORKA

Advantages of ADRIANO

- **Summary**

f_{em} Fluctuations: Consequences

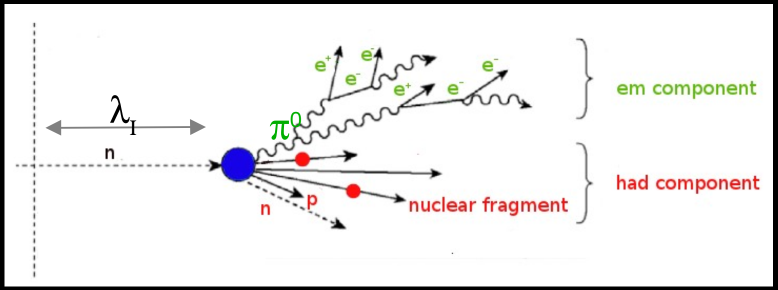
In hadronic calorimeters the fluctuations of the e.m. fraction of the shower (f_{em}) dominate the energy resolution for hadrons and jets.

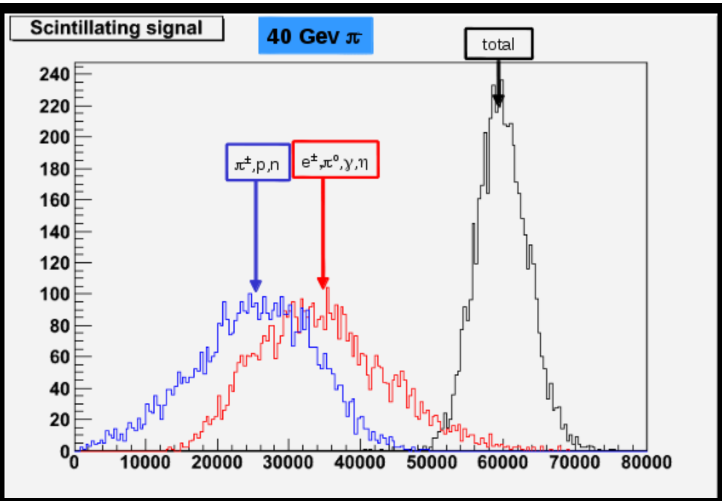
$$R = \frac{E_{measured}}{E_{shower}} = e f_{em} + h\left(1 - f_{em}\right)$$

$$f_{em} = \frac{\zeta_{EM}}{\zeta_{EM} + \zeta_{HAD}}$$

e = calorimeter response to EM shower component
h = calorimeter response to non-EM shower component

These fluctuations are due to fluctuations of the number of π^0 vs π^+





e≠h ⇨ R depends on f_{em}

What are the consequences?

- Non-Gaussian shape of hadronic response
- Non-linearity of the hadronic response
- Deviations from the $1/\sqrt{E}$ behaviour for hadronic showers

f_{em} Fluctuations: Possible Solutions

- **Compensating calorimeters (designed to have e/h=1)**

This can be achieved with hydrogenous active medium (sensitive to soft neutrons, for example plastic scintillator).
This method requires a precisely tuned sampling fraction, requiring normally a large fraction of passive medium.

- **Offline re-calibration method**

Use average shower profile information to give a different weighting of the signals as a function of the shower depths. This method gives only limited results. Insufficient when excellent resolution is required.

- **Particle flow analysis**

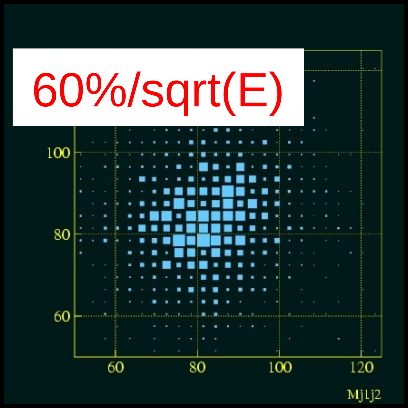
Combine information from tracking system for charged particles (~60%) and from a fine segmenteted calorimeter for neutral hadrons (~10%) (30% photons by the em calorimeter).
Gives good simulation results (....not easy to do hardware test on a large scale). Intrinsically becomes more limited at higher energies.

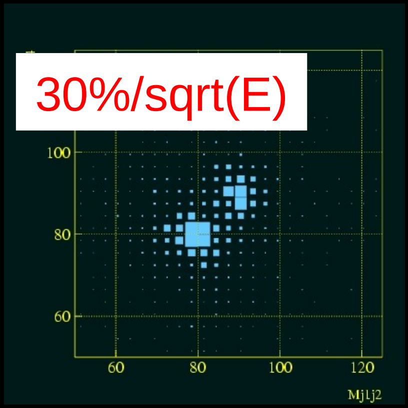
- **Dual-Readout**

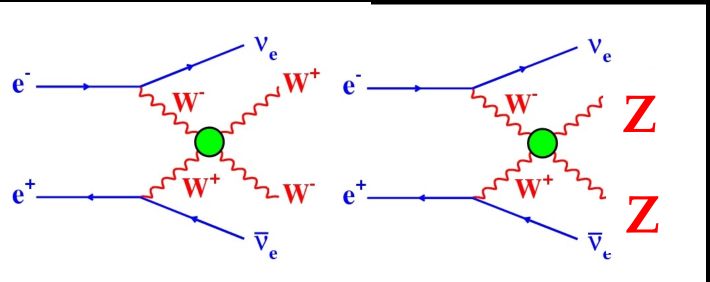
Measurement of f_{em} event by event by comparing two different signals from scintillation light and Čerencov light in the same device.

Approaches in the LC community

Two different approaches have been considered to reconstruct jets with high resolution by ILC/CLIC community to achieve the needed resolution.







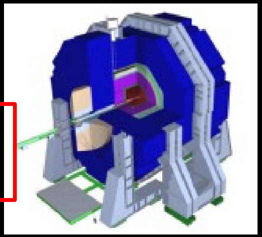
Z/W→ jj can be reconstructed and separated if

$$\sigma_E / E = 30\% / \sqrt{E(\mathrm{GeV})}$$

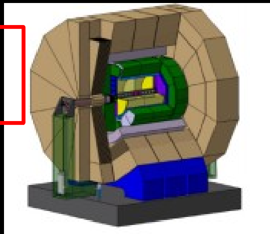
the performance goal

for the jet energy resolution

SiD



ILD



4th

- **Particle flow analysis**

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- **Dual-Readout**

  Measurement of f_{em} event by event by comparing two different signals from scintillation light and Čerencov light in the same device.

Dual-Readout Technique

The Dual-Readout is a calorimetric technique based on the simultaneous measurement of two signals generated by scintillating (S) light and Čerencov (C) light .

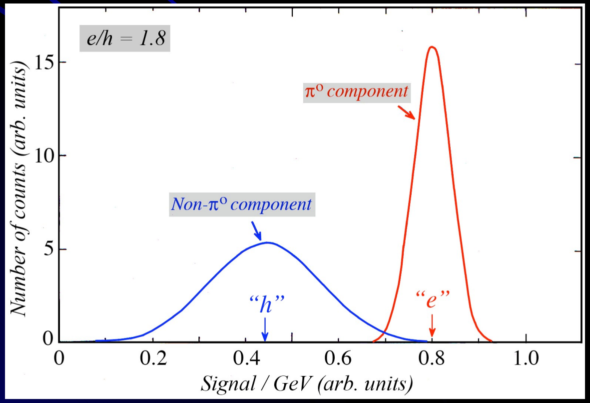
$$S = E\left[\frac{1}{\eta_S}\left(1 - f_{em}\right) + f_{em}\right]$$

$$C = E\left[\frac{1}{\eta_C}\left(1 - f_{em}\right) + f_{em}\right]$$

$$E = \frac{S - \chi C}{1 - \chi}$$

"As long as the two equations are indipendent system can be solved for the unknown f_{em} and E".
R. Wigmans

$$\eta_S = \left(e/h\right)_S \quad \eta_C = \left(e/h\right)_C \quad \chi = \frac{1 - 1/\eta_S}{1 - 1/\eta_C}$$



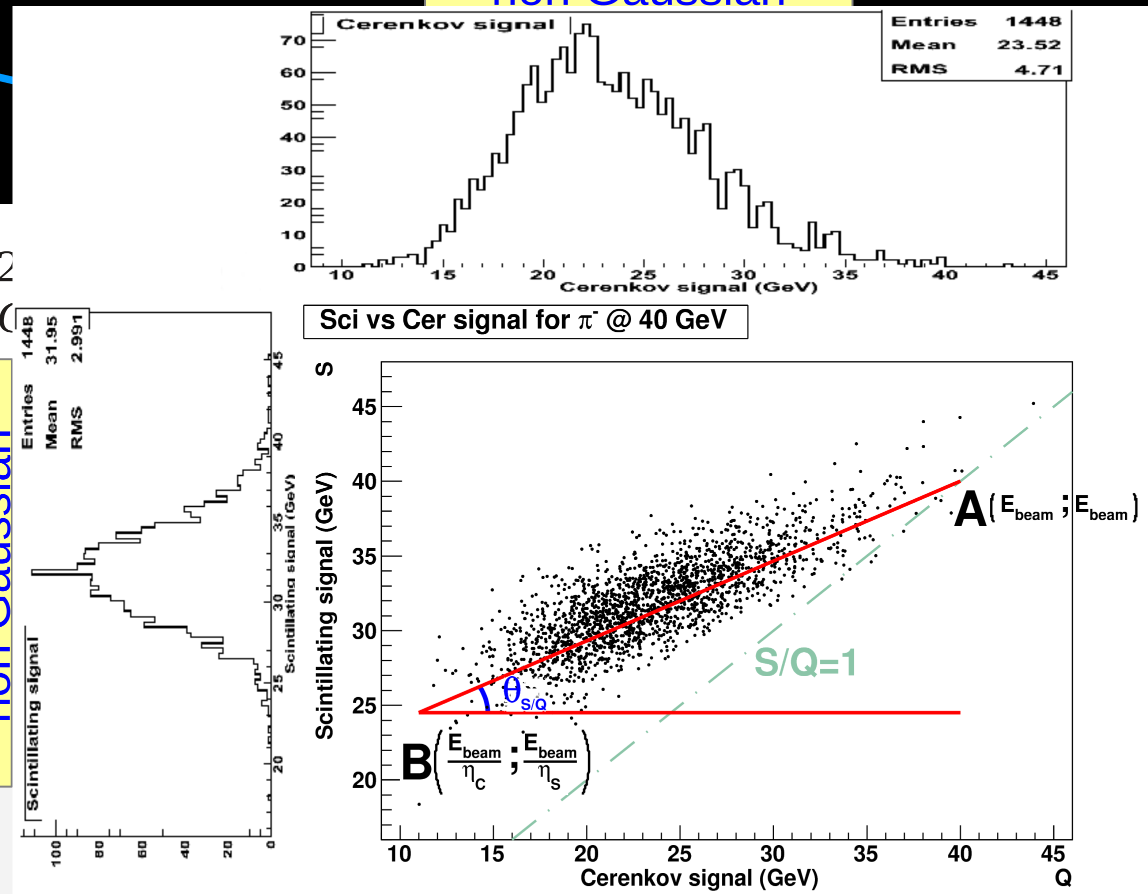
The Dual-Readout works when η_S and η_C assume different values

Dual-Readout Technique

$$E = \frac{S - \chi C}{1 - \chi}$$

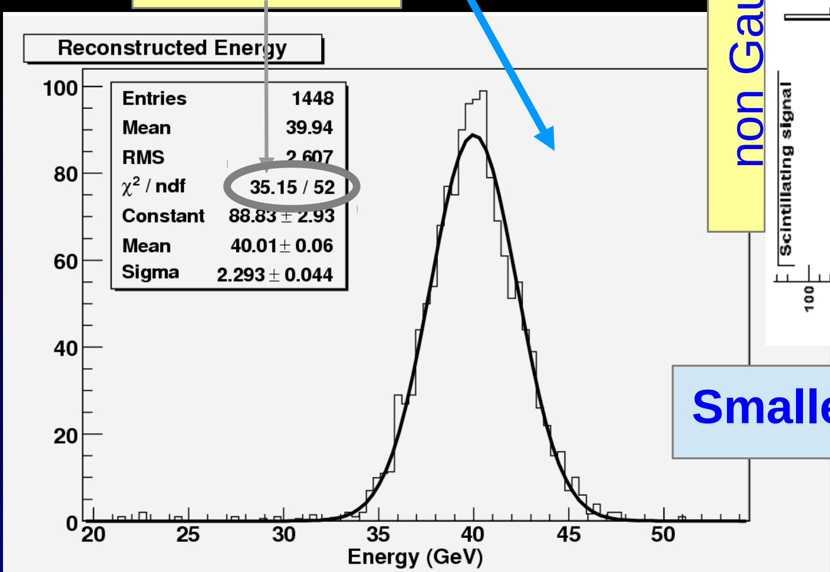
$$\sigma_E^2 = (1-\chi)^2 \sigma_S^2 + \left(\frac{\chi}{1-\chi}\right)^2 \sigma_C^2$$

non Gaussian



non Gaussian

Gaussian



Smaller the angle ϑ, smaller the σ_E^2, more precise E.

ϑ figure of merit of performance dual-deadout calorimeter.

Vito Di Benedetto's PHD thesis

Dual-Readout Calorimetry

Scintillation light is produced when charged particles pass through scintillating plastics
It is proportional to the energy deposited by the particle.
Thus is a good probe to sample the total energy of particles shower.

Čerencov light is produced when charged particles pass in a material with a speed higher than c/n.
In a hadronic shower, these particles are almost exclusevely e^+ and e^-.

Thus the two mechanisms exploit different properties of the shower

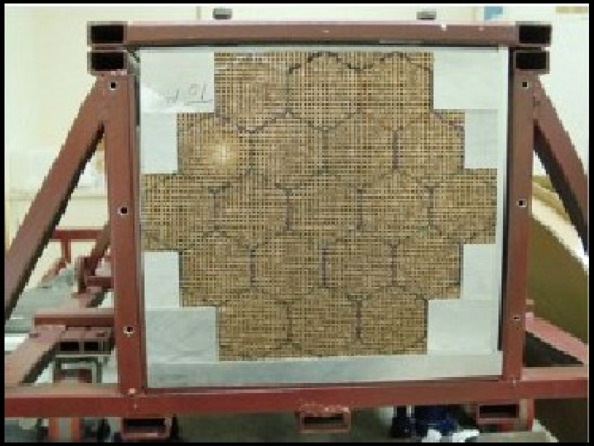
Dual-Readout calorimeter is two distinct calorimeters sharing the same absorber.
Measured energy is gaussian because of f_{em} fluctuations removed event by event.

Sampling Dual-Readout Calorimetry

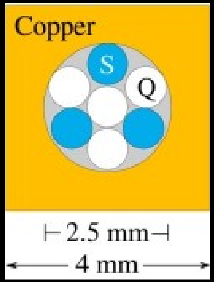
- **Sampling Dual-Readout (i.e. with PASSIVE absorber).**
- Approach pursued by **DREAM** and **4th Concept.**
  - First working example of dual-readout calorimeter.
  - Scintillation and Čerenkov light are produced in distinct and optically separated volumes.
  - Simulations consistent with test beam data and show improvement in energy resolution **up to 30%/√(E).**
  - Cheap to build (brass and plastic fibers).
  - **However very little Čerenkov light expected.**
  - **Furthermore, it requires a large amount of fibers.**

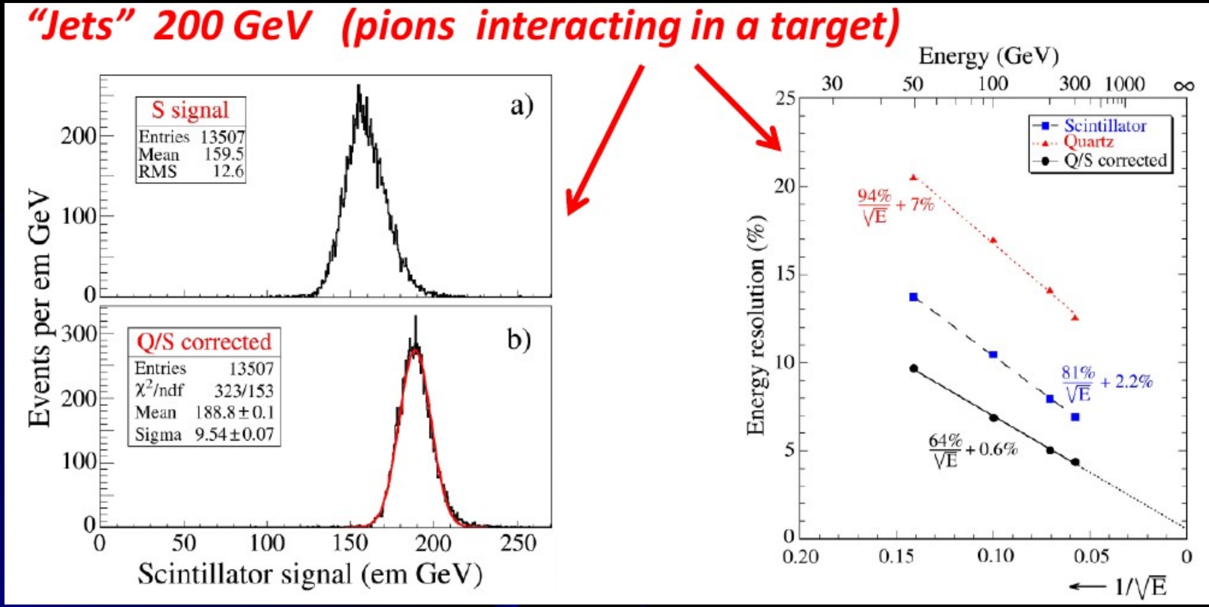
DREAM Calorimeter

First prototype implementing the Dual-Readout technique



- Copper – Scintillating and Quartz (clear) fibers
- 19 hexagonal towers,
- each tower: 270 hollow copper rods,
- 2 m (10 λ_{Int}) in depth
- radius ≈ 16 cm (< 1 λ_{Int}).

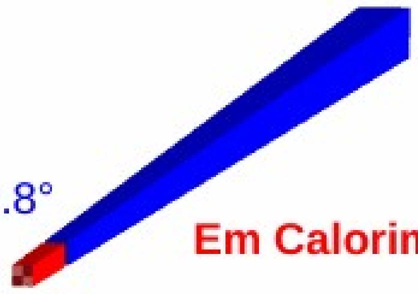


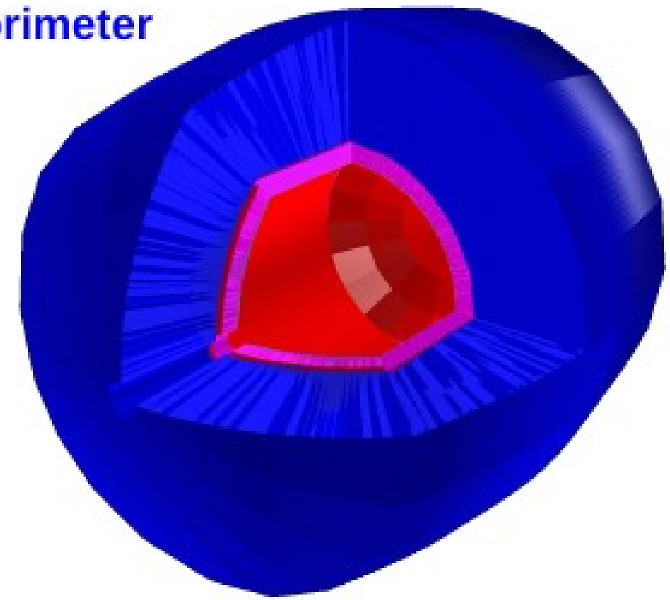


Resolution was limited by the small Cherenkov photon yield (8-18 p.e. per deposited GeV).

4th Concept Calorimeter

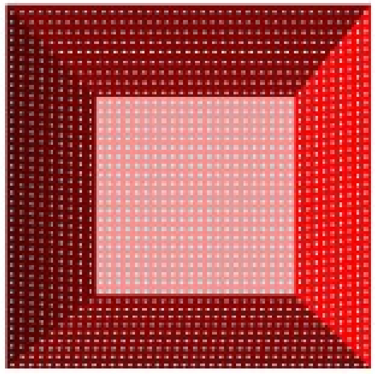
- Cu + scintillating fibers+ Čerenkov fibers
- ~1.4° tower aperture angle
- 150 cm depth
- ~ 7.3 λ_I depth
- Fully projective geometry
- Azimuth coverage down to ~2.8°
- Barrel: 16384 towers
- Endcaps: 7450 towers





Hadronic calorimeter tower

Bottom view of a tower

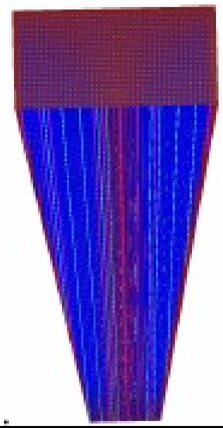


- 500 μm radius plastic fibers
- Fiber stepping ~2 mm
- Number of fibers inside each tower: ~1600 equally subdivided between Scintillating and Čerenkov

Each tower works as two independent towers in the same volume

- Top tower size: ~ 8.1 × 8.1 cm^2
- Bottom tower size: ~ 4.4 × 4.4 cm^2
- Tower length: 150 cm

Prospective view of a tower



Total Active Dual-Readout Calorimetry

- **Total Active Dual-Readout (i.e. with ACTIVE absorber).**

Approach pursued by: **DREAM** with crystals (PbWO4, BGO, ...)

T1004 with crystals (BGO, PbF2, ...)

T1015 with scintillating fibers or plates embedded in heavy glass (ADRIANO).

Next topic

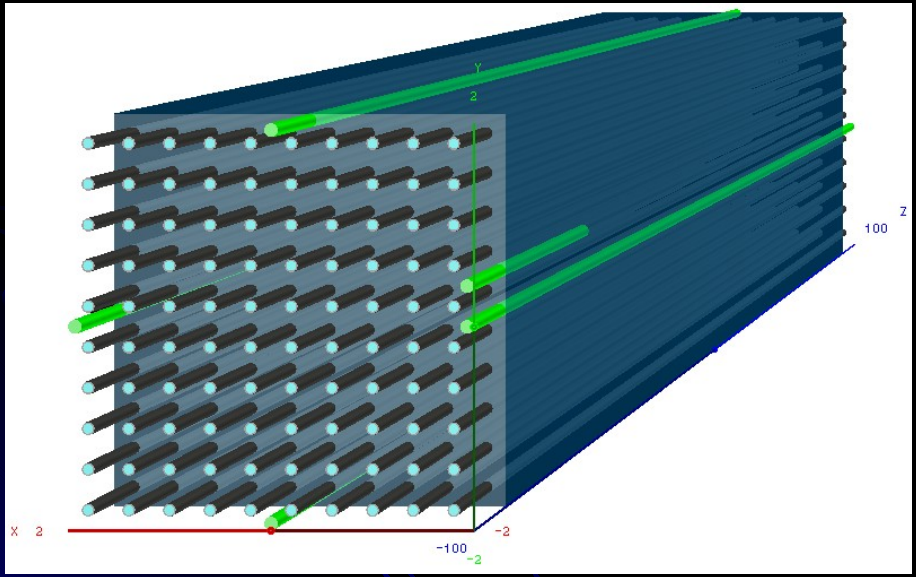
- Crystals produce both scintillating and Cerenkov light.
- Two light components have to be separated by mean of

time structure of the signals and the spectrum of the signals.

- T1015 got signals separated by design.

ADRIANO: *A D*ual-*R*eadout *I*ntegrally *A*ctive *N*on-segmented *O*ption

- Implementation of the Dual-Readout technique making use of signals from high transmittance optical glasses and scintillating fibers.



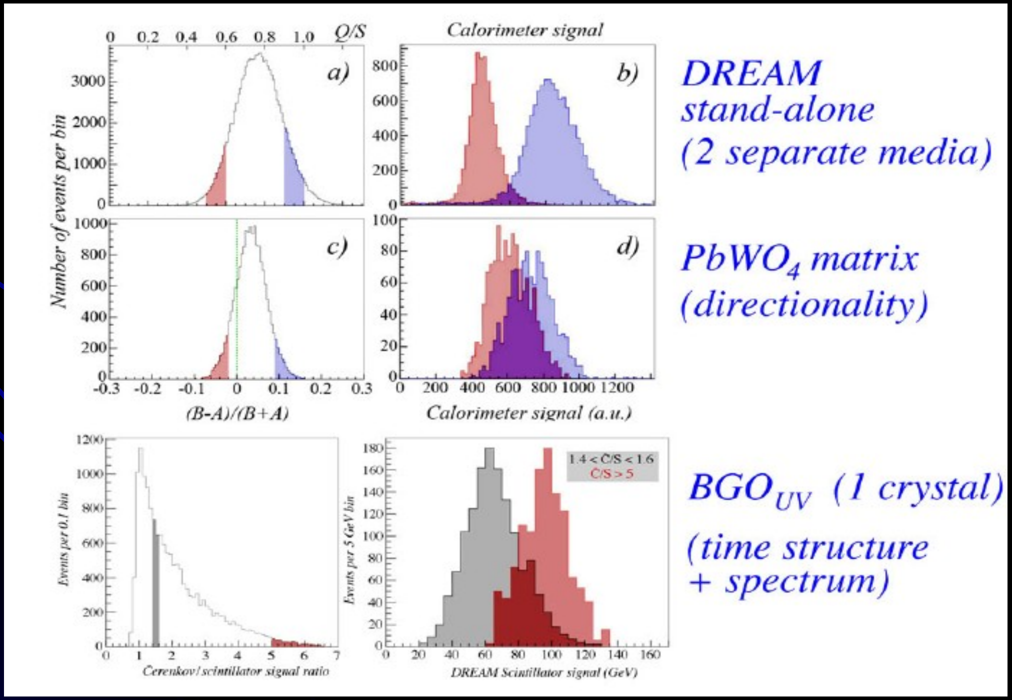
ADRIANO for a hadron calorimeter in a Muon Collider

- **Tipical cells dimensions**: 4x4x180 cm^3
- **Absorber and Cerenkov radiator**: lead glass or bismuth glass (ρ > 5.5 gr/cm^3)
- **Cerenkov light collection:** 10/20 WLS fiber/cell
- **Scintillation region**: scintillating fibers, dia. 1mm, pitch 4mm (total 100/cell) optically separated from absorber
- **Particle ID**: 4 WLS fiber/cell (black painted except for foremost 20 cm)
- **Readout**: front and back SiPM (Scifi only)
- **CoG z-measurement**: light division applied to SCSF81J fibers (same as CMS HF)
- **Small tg($\theta_{S/Q}$)**: due to WLS running longitudinally to cell axis ($\theta_{Cerenkov}$ < 90 - θ_{Snell} for slower hadrons).

Rationale #1 for *ADRIANO*

- **Scintillating and Cerenkov light in *OPTICALLY SEPARATED MEDIA:***
  → non-homogeneous detector
  - ***Use the absorber as Cerenkov component of dual-readout***
  - ***Use scintillating fibers for the second component***
  - ***Control the scintillation/Cerenkov with appropriate pitch between fibers***

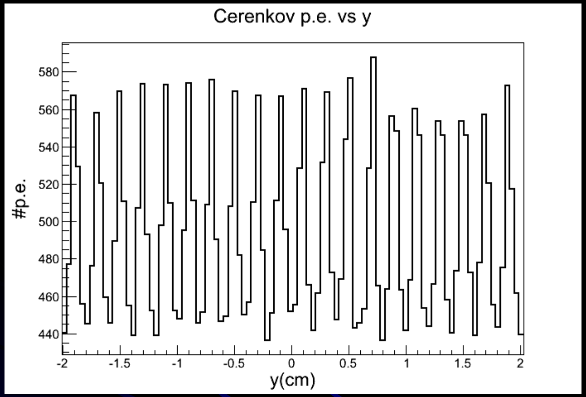
Separation efficiency between S & C components



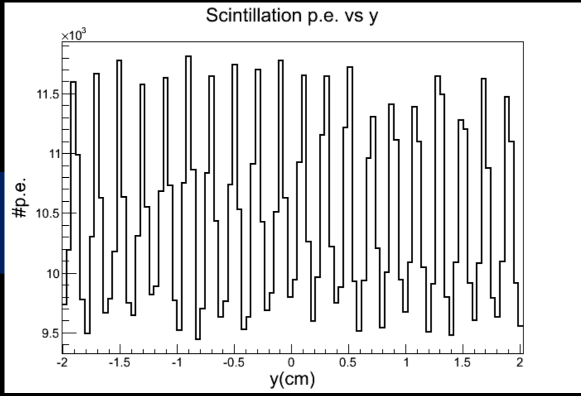
Report form DREAM Collaboration studies.

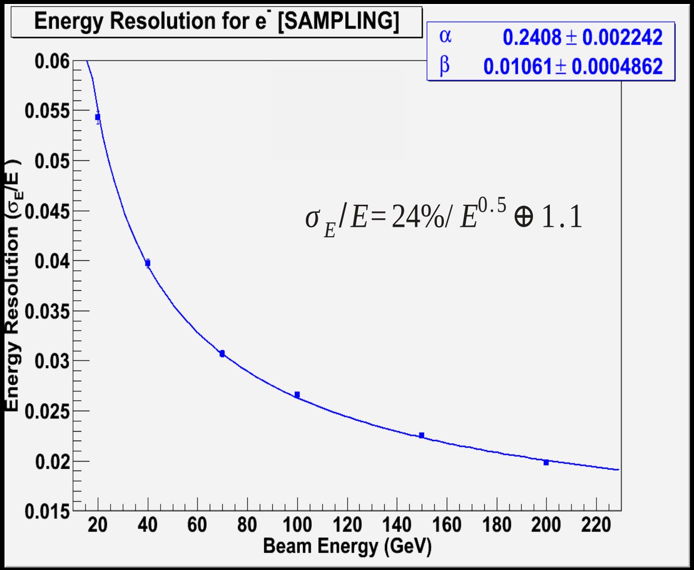
Rationale #2 for *ADRIANO*

- **Integrally Active Calorimeter with transparent, high n_D absorber**
  - Use homogeneous medium as an ACTIVE ABSORBER
  - It generates the Cerenkov component of dual-readout at the same time
  - Lots of Cerenkov photons when n_D is about 2.0 or greater
  - Avoid sampling frequency fluctuations for EM showers



C and S from horizontal beam scan in a sampling calorimeter





Cerenkov and Scintillating signal produced by e^- @ 45 GeV beam in sampling dual readout calorimeter with 1mm pitch between fibers as function of e^- impact point.

Rationale #3 for *ADRIANO*

- **Use heavy glasses rather than crystals**

	Glass	Crystals
Light production mechanism	Only Cerenkov (minor fluorescence with some SF glasses)	Cerenkov + scintillation
Stability vs ambiental (temperature, humidity, etc)	Excellent	Varies, but generally poor
Stability vs purity	Very good if optical tranmittance is OK	Very poor
Longitudinal size	Up to 2m	20-30 cm max
Cost	0.4-0.8 EUR/cm^3	10-100 EUR/ cm^3
Time response	prompt	Slow to very slow (with exceptions)
n_d	1.85-2.0 (commercially available) 2.25 (experimental)	1.85-2.3
Density	6.6 gr/cm^3 (commercially available) 7.5 gr/cm^3 (experimental)	Up to 8-9 gr/cm^3
Radiation hardness	Medium (recoverable via UV annealing for Pb-glass) or unknown (for Bi-glass)	varies

Rationale #4 for *ADRIANO*

- Keep **the number of fibers to as manageable level** for a 4π calorimeter
- Define Γ = total area of photodetector/total external calorimeter area.
- Γ takes into account:

  - The needed photodetector area to read circular fibers with optimum packing

  - The crowdiness of your FEE
- At present:
  - Γ_{DREAM} = ~24%; $\Gamma_{4th\ Concept}$ = ~ 21%; Γ_{Spacal} = ~ 21%

Quite large

➢ **In its baseline configuration $\Gamma_{Adriano}$ = 8%**

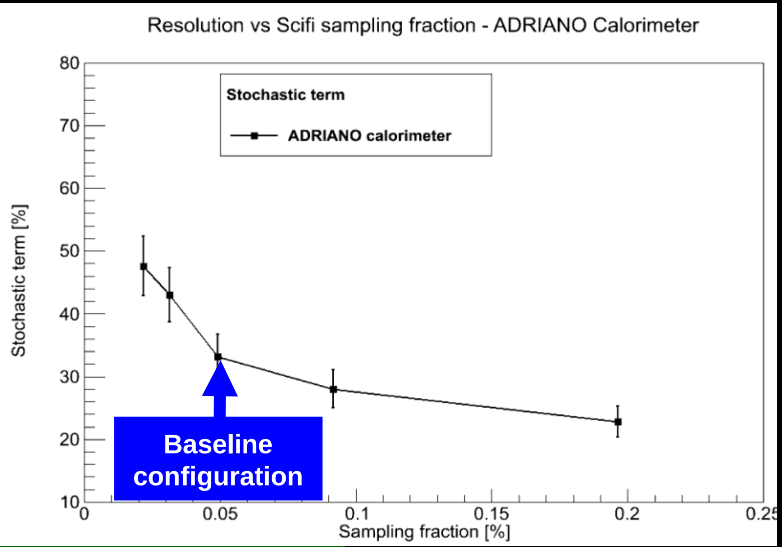
ADRIANO expected Light Yield and Resolution

Integrally Active with Double side readout (*ADRIANO*)

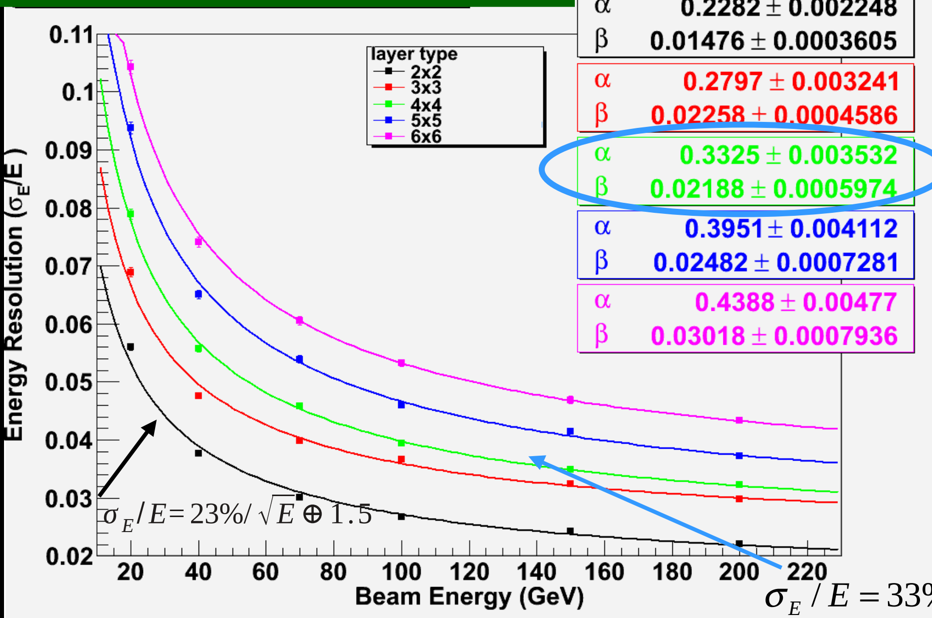
Pitch [mm²] Diameter	2x2 1mm	3x3 1mm	**4x4 1mm**	5x5 1mm	6x6 1mm	4x4 1.4mm	4x4 2mm	4x4 capillry	Sampling
$<pe_S/GeV>$	1053	430	**254**	163	124	500	110	250	200
$<pe_C/GeV>$	340	360	**360**	355	355	355	350	350	7.5

Baseline configuration (4x4 1mm)

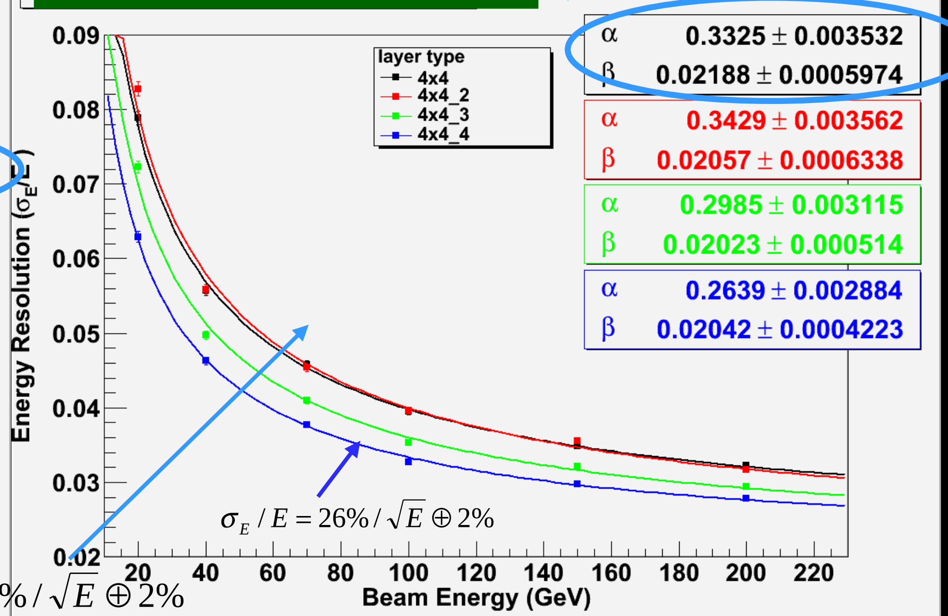
1-side readout (Sampling)



Fiber pitches: 2mmx2mm through 6mmx6mm



fiber diameter: 1mm – 1.4mm – 2 mm

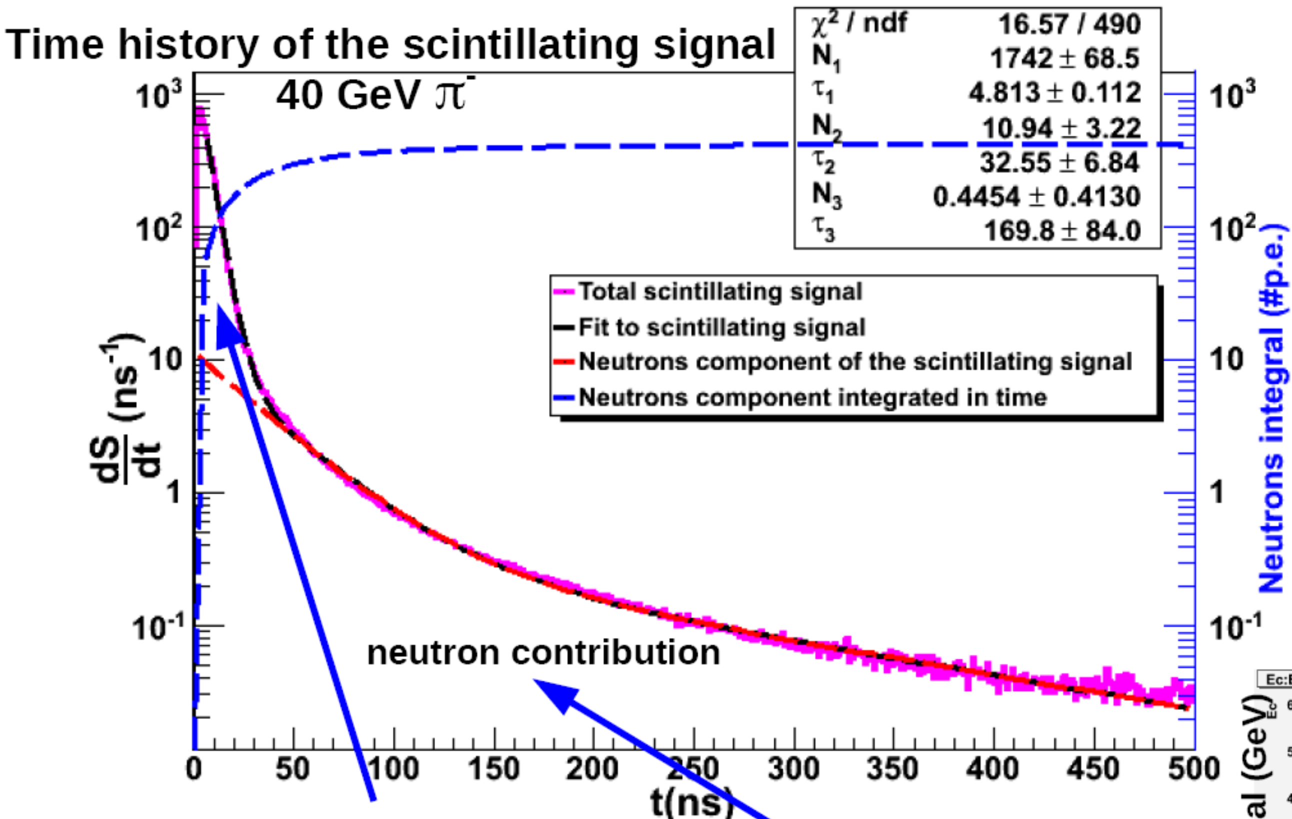


All numbers include the effect of photodetector QE

ILCroot simulations

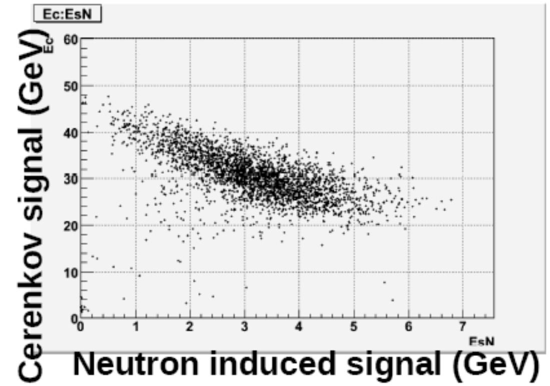
From Dual to Triple Readout

Disentangling neutron component with waveform analysis



After 50 ns
only neutrons
contribute to the
scintillating signal

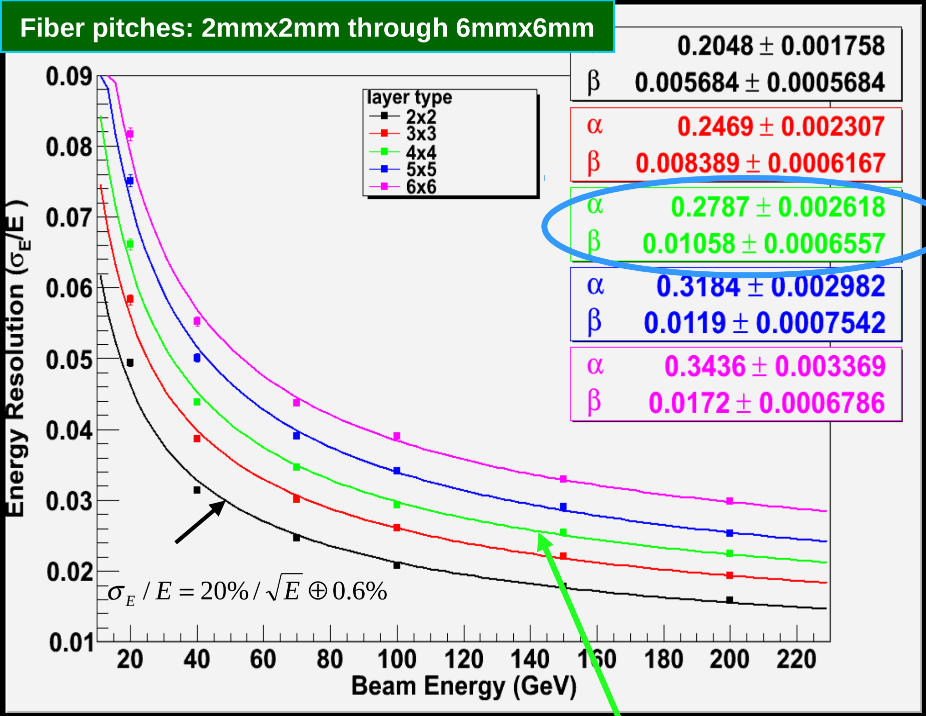
$$E_{shower} = \frac{S_{fast} - \chi C}{1-\chi} + \xi S_{slow}$$



Vito Di Benedetto's PHD thesis

ADRIANO in Triple Readout configuration

Fiber pitches: 2mmx2mm through 6mmx6mm



Baseline configuration

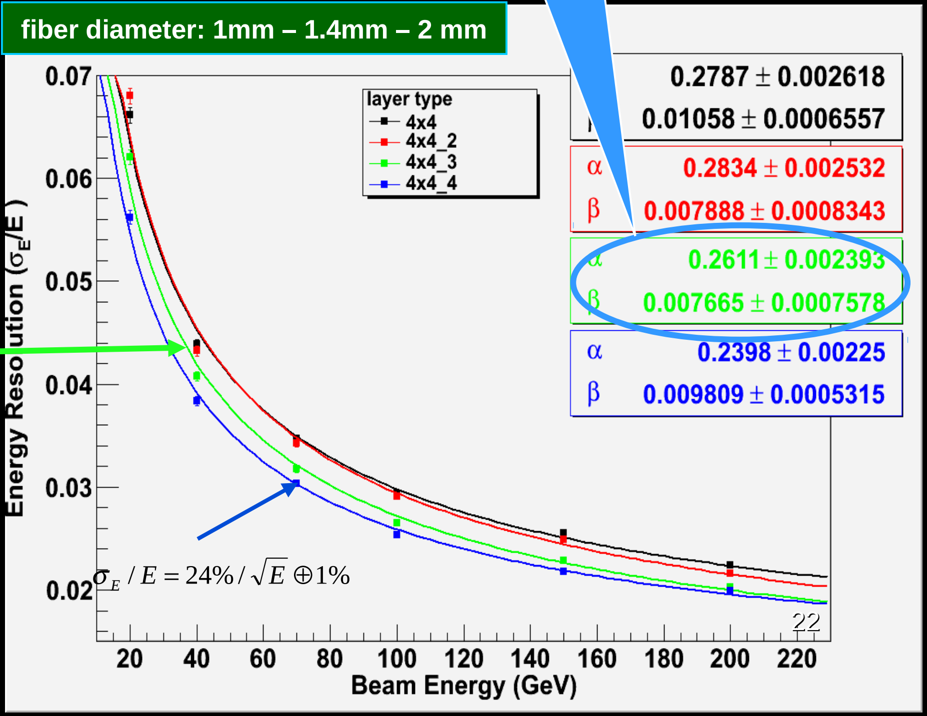
$$\sigma_E / E = 28\% / \sqrt{E} \oplus 1$$

Compare to ADRIANO in Double-Readout configuration

$$\sigma_E / E = 33\% / \sqrt{E} \oplus 2$$

Pion beams

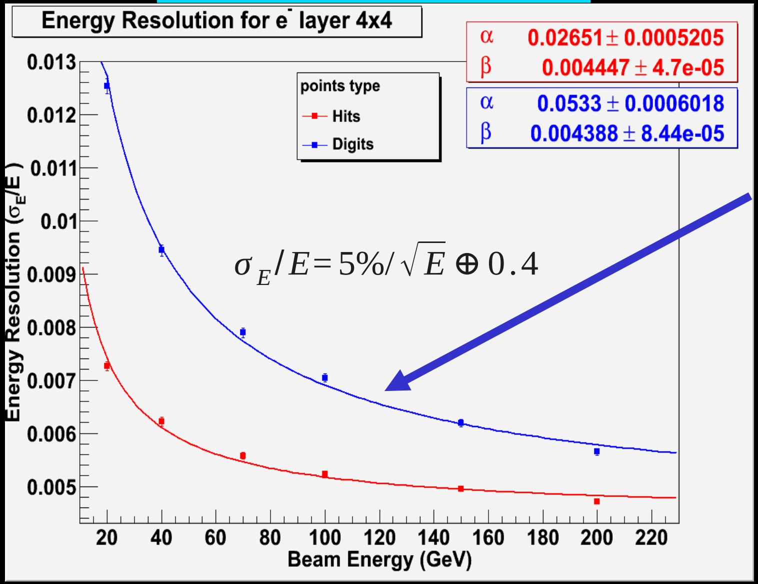
fiber diameter: 1mm – 1.4mm – 2 mm



ADRIANO EM Resolution (with and without instrumental effects)

- Compare standard Dual-readout method vs Cerenkov signal only (after electron-ID).
- Blue curve includes instrumental effects. Red curve is for perfect readout.

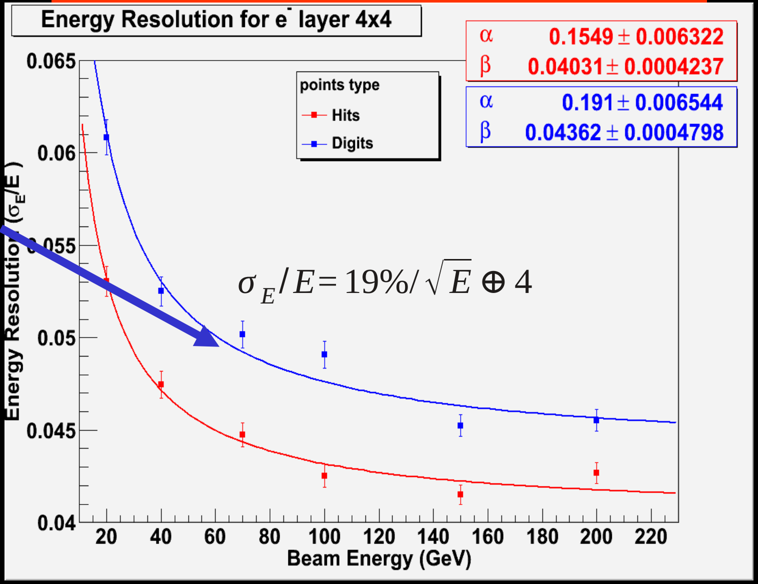
Use only Cerenkov light



Blue curve includes:

- **SiPM's ENF**
- **Constant noise**
- **Fiber non-uniformity**
- **14 bit ADC**
- **3pe threshold**

Dual-readout (scintillating+Cerenkov)

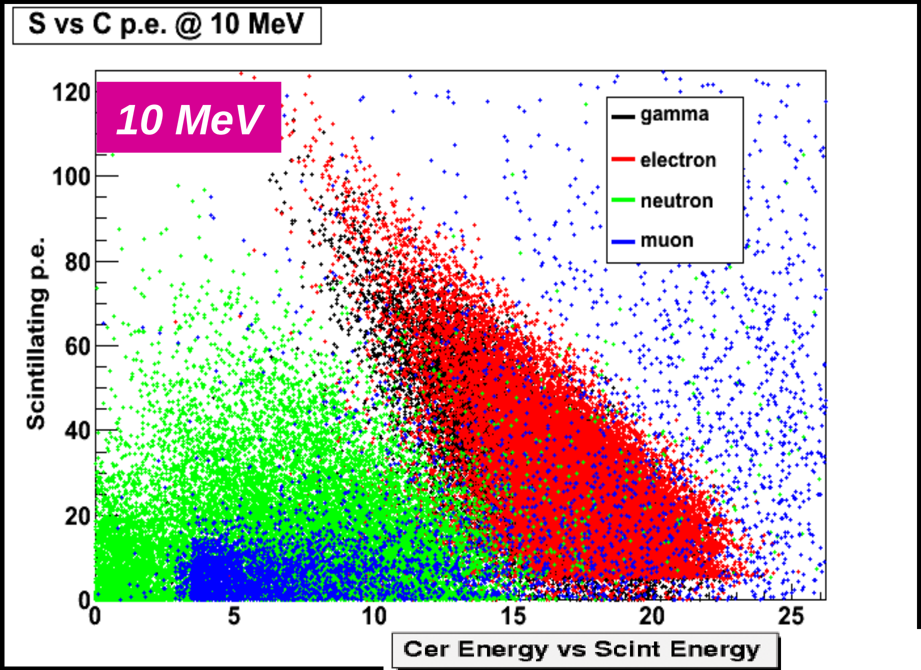


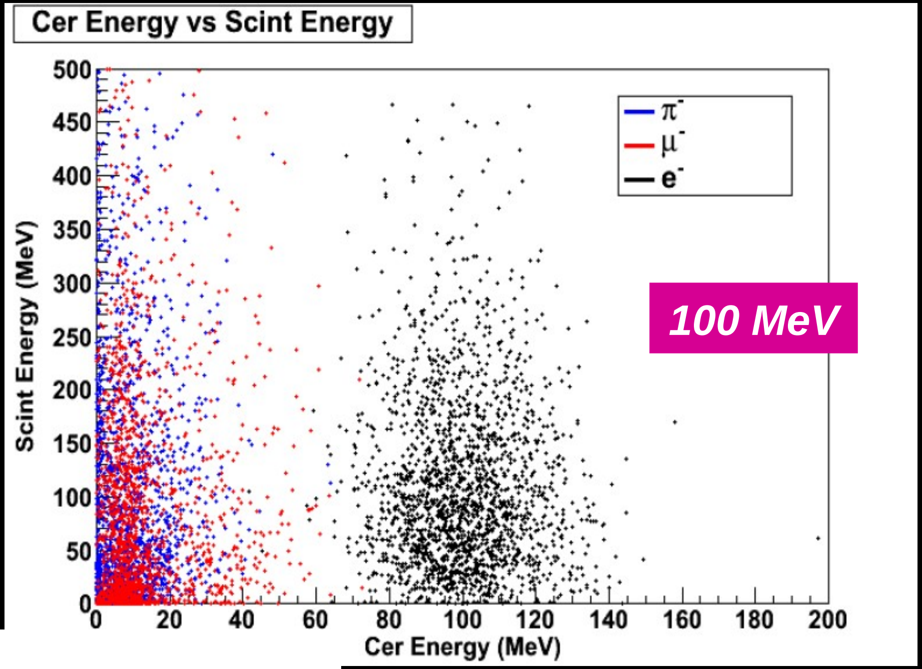
Using Cerenkov signal only for EM showers gives **5%/√E** energy resolution while full fledged dual-readout gives only **19%/√E** (including FEE effects)

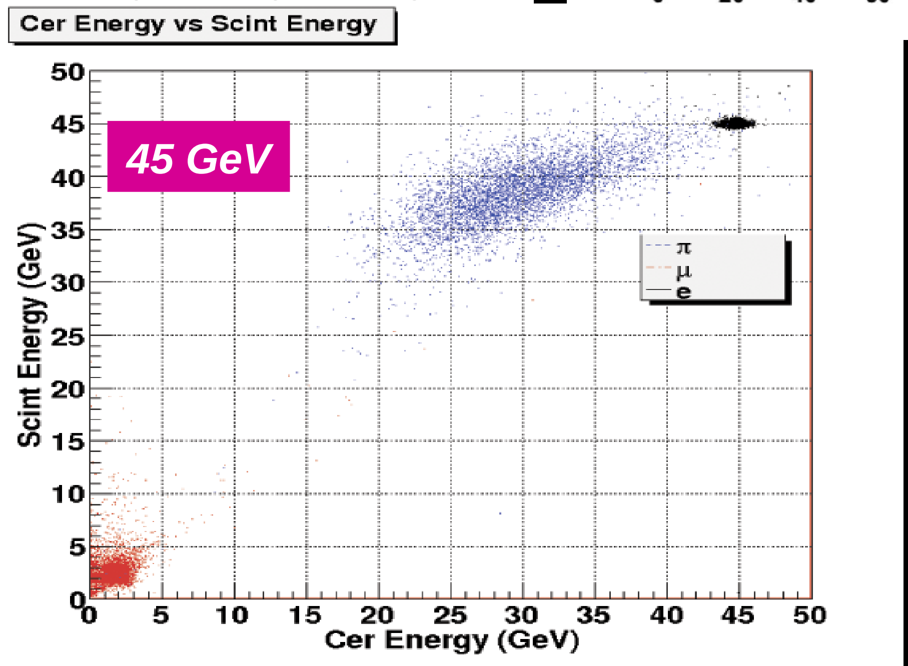
ADRIANO does not need a front EM section

If Cerenkov ligth yield is large enough

Particle ID with ADRIANO



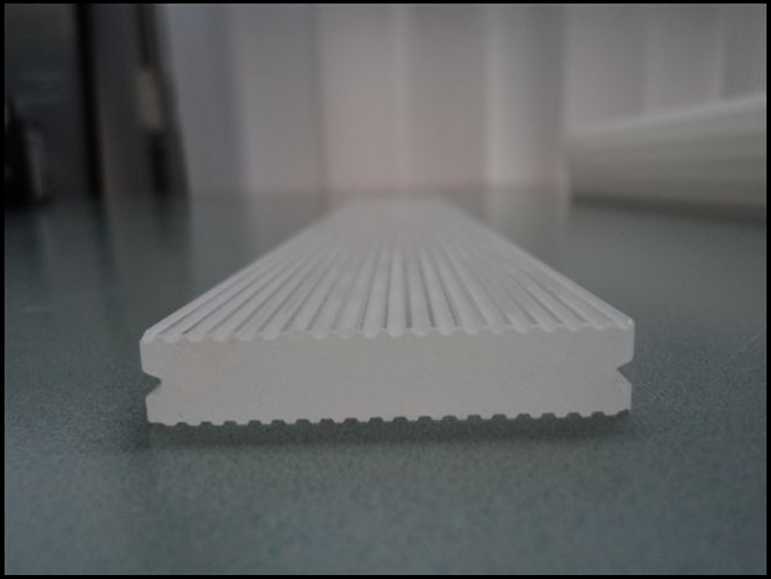




Fabrication Technology #1: Diamond tools machining

- Pro
  - ***Minimal R&D required***
  - ***Room temp (min effect on n_D)***
  - ***It allows construction of longer cells***

- Cons
  - ***Longer fabrication process***
  - ***Large waste***



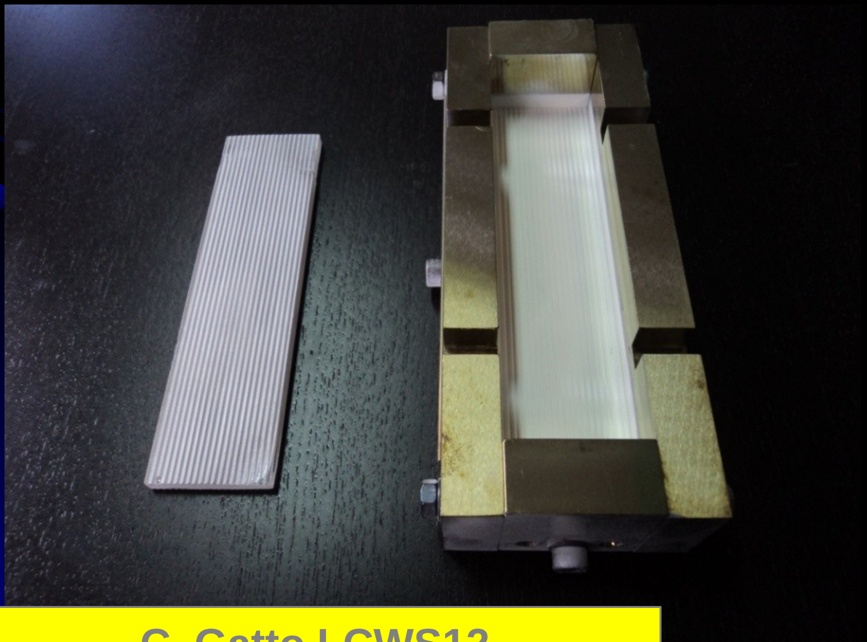
C. Gatto LCWS12

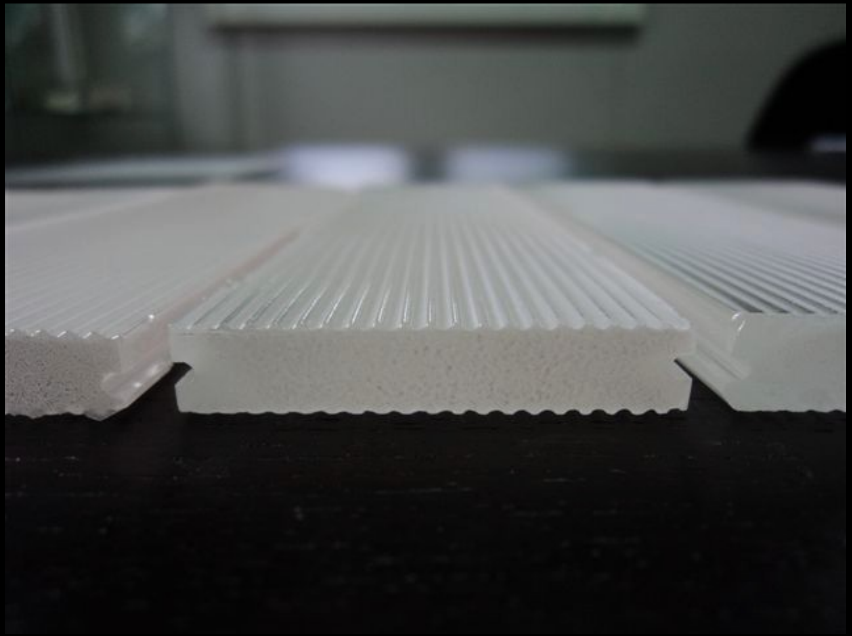
SALENTEC advanced technologies

Fabrication Technology #2: Precision molding

- Pro
  - ***Cheapest and fastest (15 min)***
  - ***Optical finishing with no extra steps***
  - ***Low temp cycle (min effect on n_D)***

- Cons
  - ***Molds are expensives***
  - ***Lots of R&D***



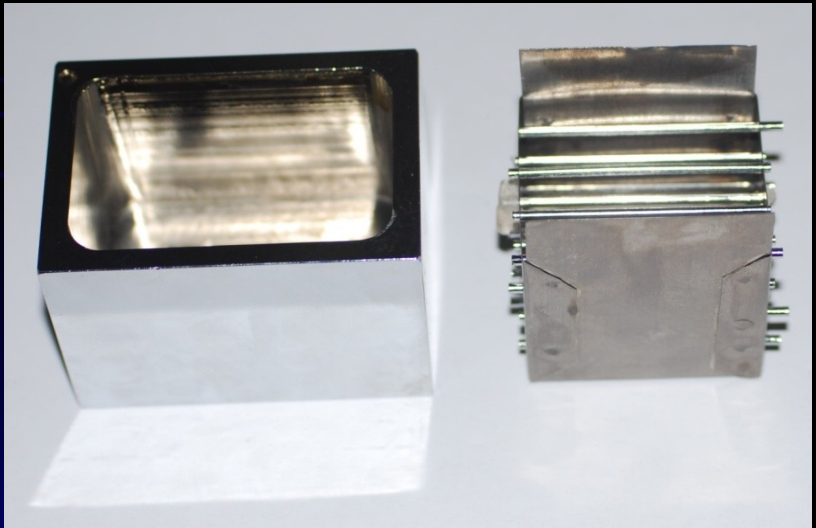


C. Gatto LCWS12

Fabrication Technology #3: Glass melting

- Pro
  - ***Build entire cell in one step***
  - ***Very robust mechanical structure***

- Cons
  - ***High temperature cycle***
  - ***Extra passive material***
  - ***Easy to get glass defects***



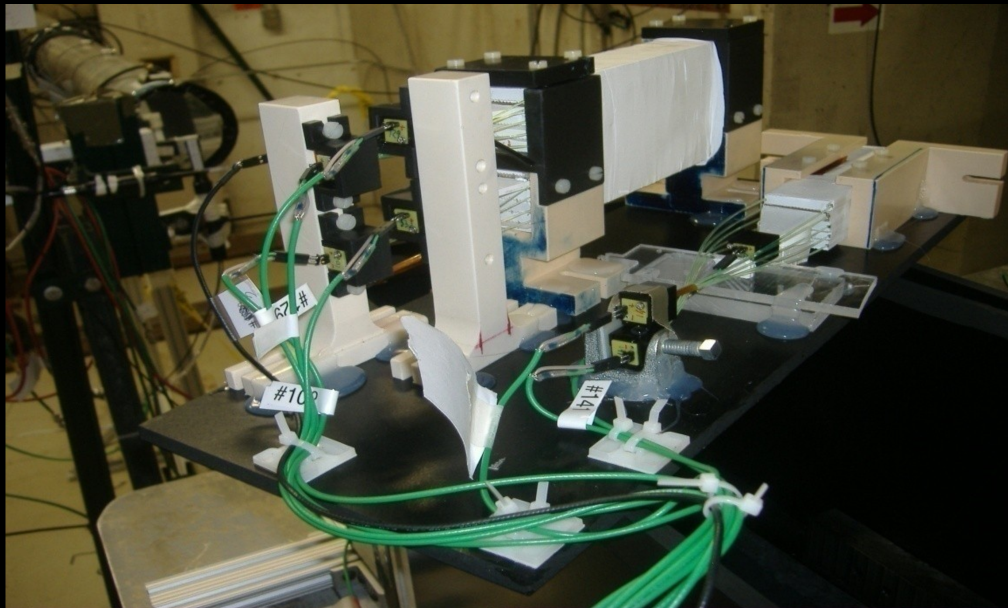
ADRIANO In T1015 R&D Program

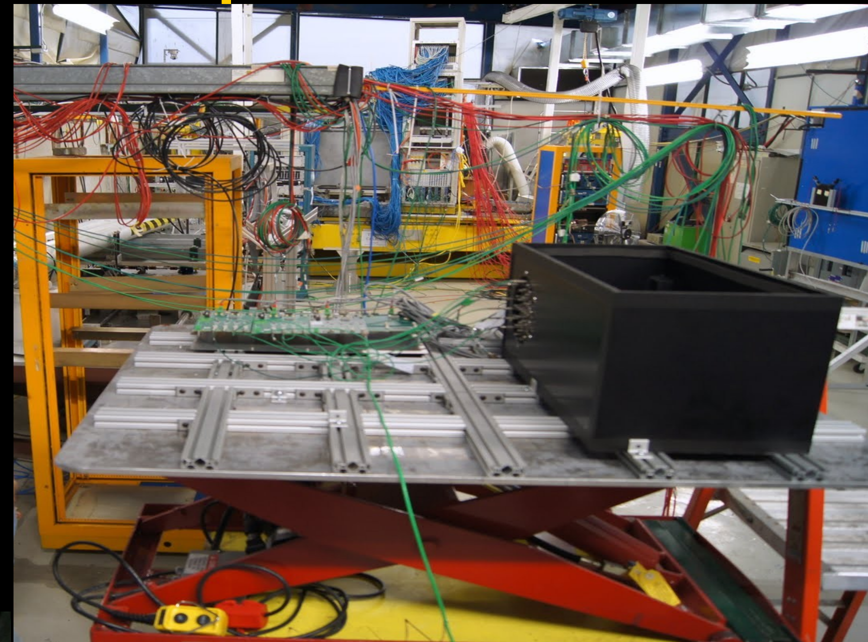
- Four tests beam at FTBF in 2011-2012: several cells in different configurations (40x40x250 mm^3)
- 4 glass type: lead and bismuth based + scintillating Ce doped glass
- 3 glass coatings: TiO2, Silver paint, clear acrylic
- 3 WLS fibers: Y11 (1.2mm) & BCF92 (1.0, 1.2 mm)
- 1 Scintillating fiber: SCSF81
- 4 scifi coating: TiO2, BasO4, Silver paint, Al sputter
- Several optical glues (mostly homemade)
- 5 photodetectors: 2 SiPM (2.8 round and 4.3x4.3 square) & 2 PMT (P30CW5 , R647, H3165)
- 4 light coupling systems: direct glass + direct WLS + 4 light concentrators

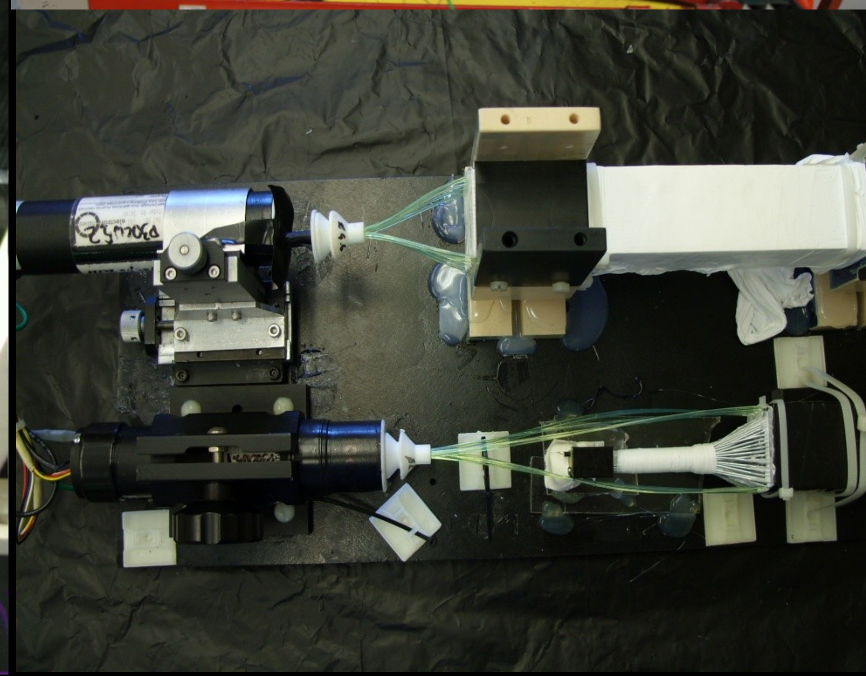
Goals :

- ***Maximize light yield (Cerenkov)***
- ***Measure parameters for Monte Carlo simulations***

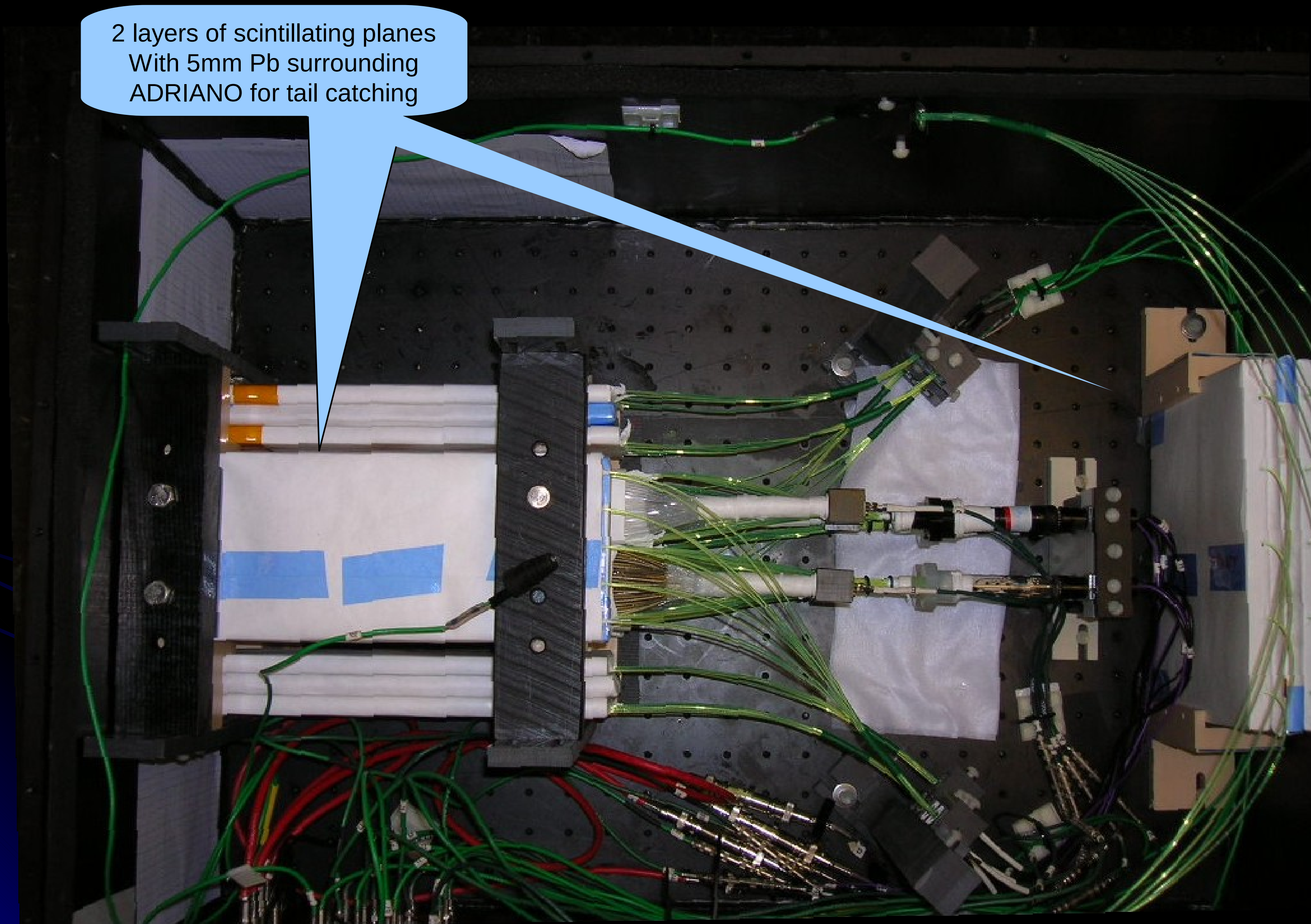
2011 Test Beam Setup at FTBF







2012 Test Beam Setup at FTBF



Preliminary

11 Prototypes Performance Summary

Prototype	Glass	gr/cm^3	L. Y.	Notes
5 slices, machine grooved, unpolished, white	**Schott SF57HHT**	**5.6**	82	SiPM readout
5 slices, machine grooved, unpolished, white, v2	**Schott SF57HHT**	**5.6**	84	SiPM readout
5 slices, precision molded, unpolished, coated	**Schott SF57HHT**	**5.6**	55	15 cm long
2 slices, ungrooved, unpolished, white wrap	**Ohara BBH1**	**6.6**	65	
5 slices, scifi silver coated, grooved, clear, unpolished	**Schott SF57HHT**	**5.6**	64	15 cm long
5 slices, scifi white coated, grooved, clear, unpolished	**Schott SF57HHT**	**5.6**	120	
10 slices, white, ungrooved, polished	**Ohara PBH56**	**5.4**	30	DAQ problems
10 slices, white, ungrooved, polished	**Schott SF57HHT**	**5.6**	76	
5 slices, wifi Al sputter, grooved, clear, polished	**Schott SF57HHT**	**5.6**	30	2 wls/groove
5 slices, white wrap, ungrooved, polished	**Schott SF57HHT**	**5.6**	158	Small wls groove
2 slices, plain, white wrap	**Ohara experimental**	**7.5**		DAQ problem

- Analysis still ongoing
- Calibration problematic for DAQ issues and degrading of PMTs from He leaks
- Need further confirmation of the results

ADRIANO For ORKA

- Proposed a revisited version of ADRIANO calorimeter for ORKA photon veto Barrel.
- It uses lead glass and scintillator tiles instead of fibers used for teh high energy version.
- Two options under study:

  A) ADRIANO in dual-readout mode

  Optimized for low energy photons

  PID and lowest accidentals (require coincidence between Scintillation and Cerenkov)

  Higher costs

  Preliminary studies presented in this talk

  B) ADRIANO in single readout mode

  No PID and worse energy resolution

  Lower costs

  Extensive R&D required

- Intense simulation activity already started using IlcRoot framework.

ORKA at Fermilab

- Aim: 1000 Event Measurement of $K^+ \to \nu\nu$ at FNAL Main Injector.
 - 5σ reach for B>1.3 BSM.
 - 10x higher sensitivity than CERN NA62.
- Proven technique based on the successful BNL E787/E949 experiments.
- Re-use of Fermilab infrastructure: CDF magnet/hall.
- R&D underway.
- ORKA was granted scientific approval from Fermilab in December 2011.
- Total Project cost estimate: <$80M (FY2013).

The ORKA Collaboration

- Seventeen institutes from six nations: Canada, China, Italy, Mexico, Russia, USA
- Seven US universities now.
- Two US National Laboratories

ORKA Siting Options

Most promising option

B0:

-Rad hard transport,
requires A0 to B0 line.
-Resident magnet & cryo
-Infrastructure

Sea-Quest/NM4:

-Existing beam transport,
Adequate Shielding?
-Infrastructure at NM4
but no cryo.

Meson Detector Building/NM4:

-Use one beam line,
Adequate Shielding?
-Infrastructure at NM4
additional cryo.

ORKA Motivation

1. The branching ratio is sensitive to most New Physics (NP) models. This sensitivity is unique in quark flavor physics and allows probing of essentially all models of NP that couple to quarks within the reach of the LHC. Furthermore, a high precision measurement $K^+ \rightarrow \pi^+ \nu\nu$ is sensitive to many models of with mass scales well beyond the direct reach of the LHC.

2. The Standard Model (SM) predictions for the $K^+ \rightarrow \pi^+ \nu\nu$ and $K^0 \rightarrow \pi^0 \nu\nu$ branching fractions are broadly recognized to be theoretically robust at the 5–10% Level.

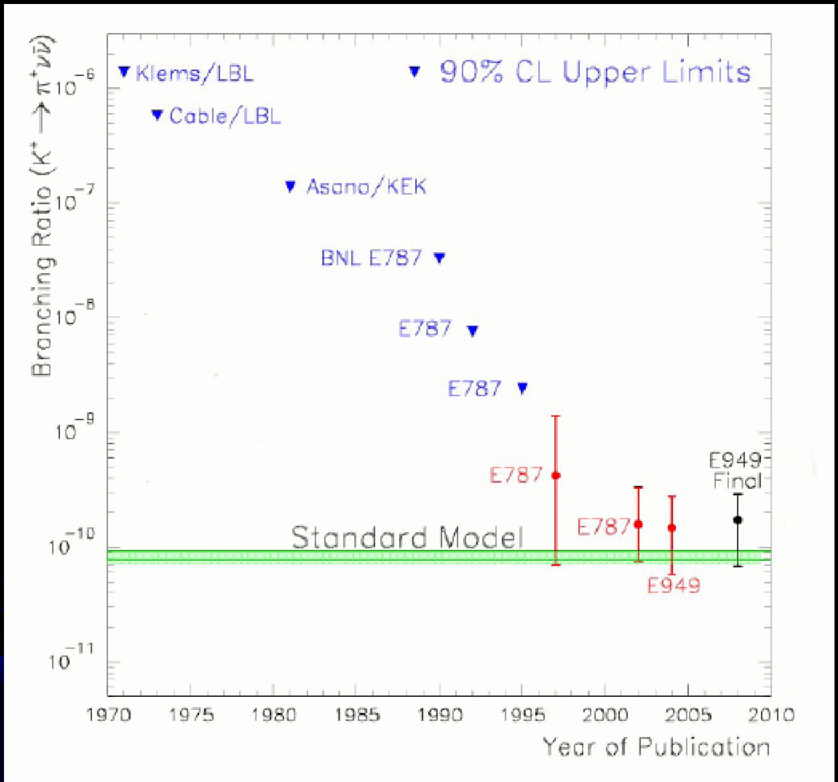
3. Because the $K^+ \rightarrow \pi^+ \nu\nu$ branching ratio is highly suppressed in the SM (to the level of < 1 part in 10 billion) NP can compete and be observed with enhancement factors of up to five times the SM value. In addition, the certainty with which the SM Contribution.

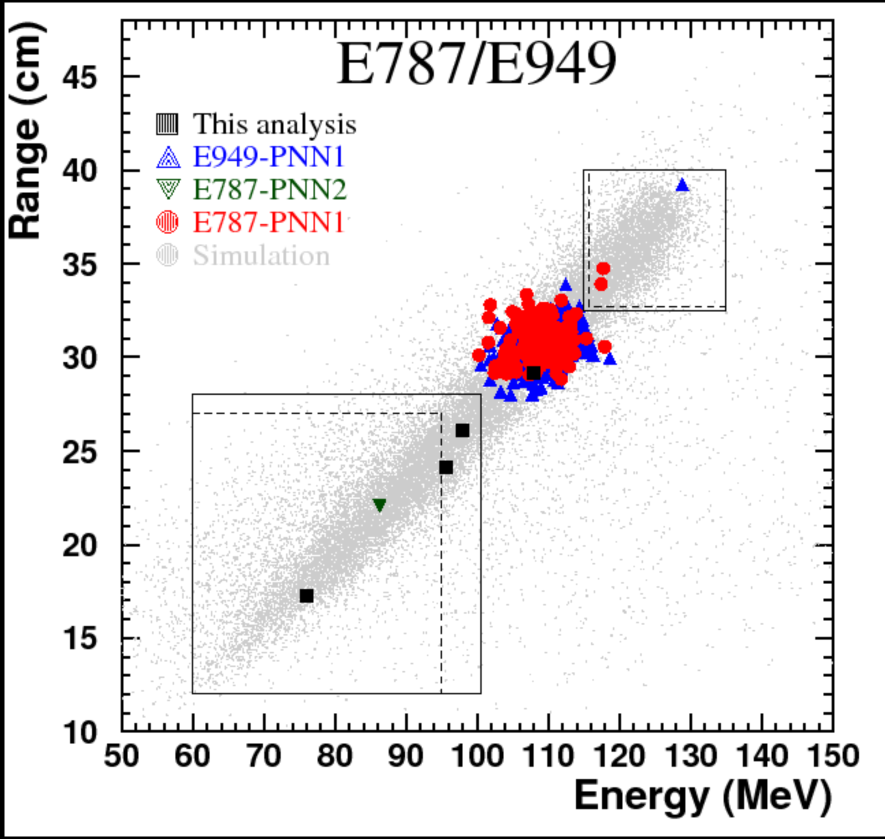
4. Morover the certainty with which the Standard Model contribution to $K^+ \rightarrow \pi^+ \nu\nu$ can be predicted will permit a 5σ discovery potential for new physics with just a 35% deviation from the SM.

Access to NP at and beyond LHC mass scale.

Special status: small SM uncertainty and large NP reach.

$K^+ \to \pi^+ \nu\nu$ History





E787/E949 Final: 7 events observed

$$B(K^+ \to \pi^+ \nu\nu) = 1.73^{+1.15}_{-1.05} x10^{-10}$$

Standard Model:

$$B(K^+ \to \pi^+ \nu\nu) = (0.78 \pm 0.08) x10^{-10}$$

Experimental Challenges

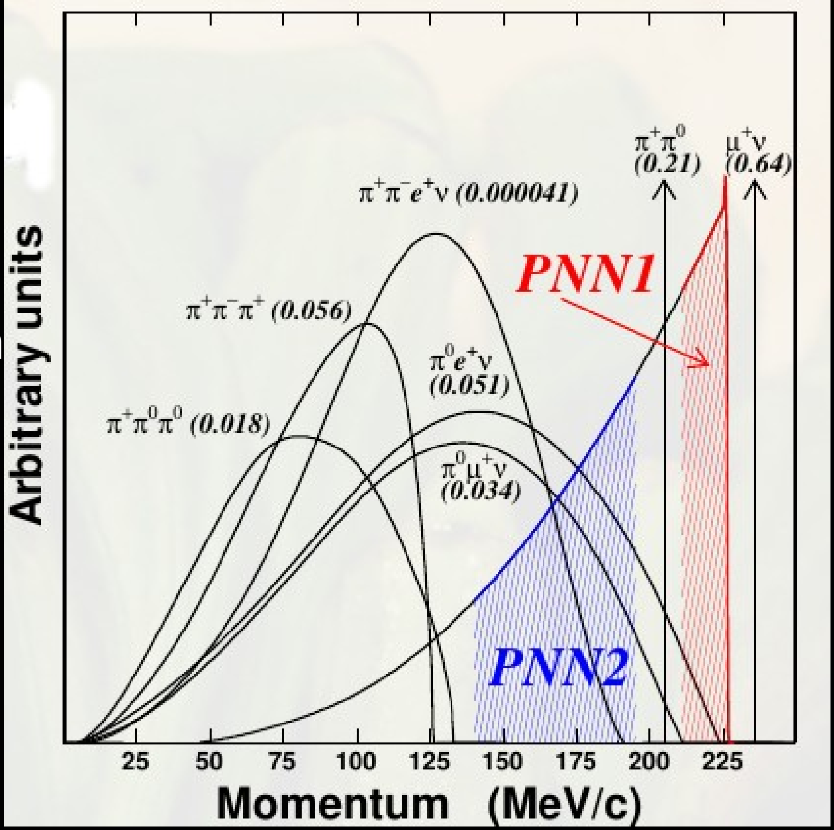
Experimentally weak signature with background exceeds signal by 10^{10}

To successfully detect $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and separating it from background, the detector must have:

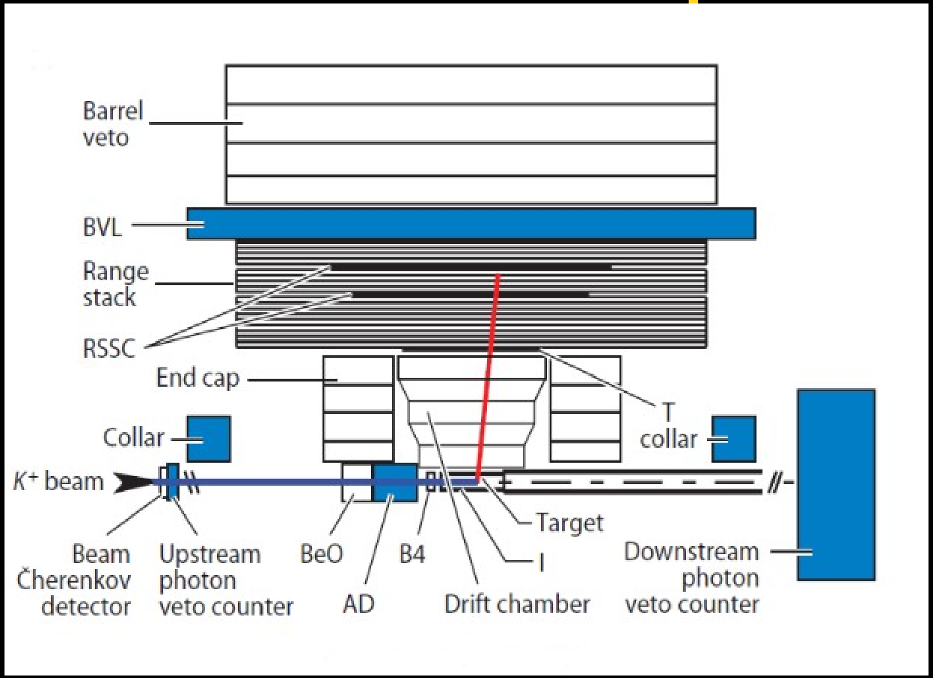
- Powerful π^+ particle identification ($\pi^+ \rightarrow \mu^+ \rightarrow e^+$) so that $K^+ \rightarrow \mu^+ \nu_\mu$ ($K\mu2$) and $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ ($K\mu2$) decays can be rejected.

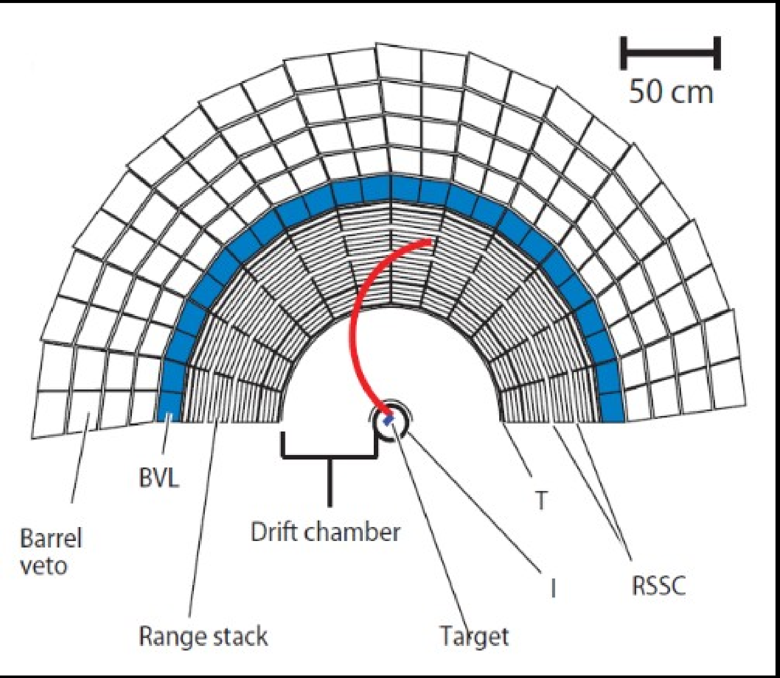
- Highly efficient 4π solid-angle photon detection coverage for vetoing $K^+ \rightarrow \pi^+ \pi^0$ ($K\pi2$) events and other decays.

- Efficient K^+ identification system for eliminating beam-related backgrounds.



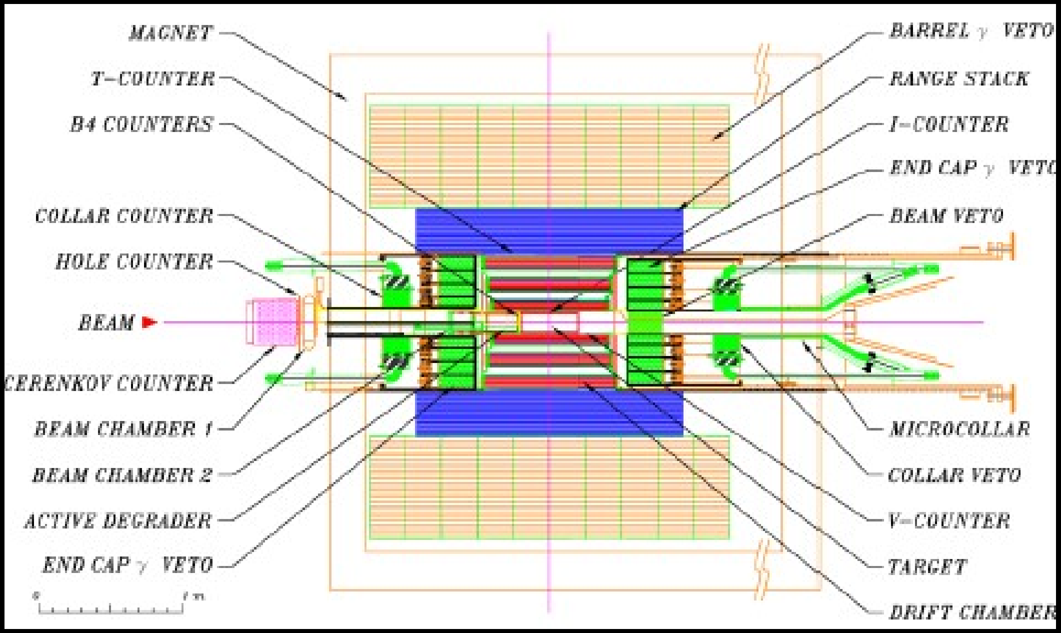
E949 Experimental Method





- 710 MeV/c K^+ beam.
- Stop K^+ in scintillating fiber target.
- Wait at least 2 ns for K^+ decay to suppress prompt background.
- Measure π^+ momentum in drift chamber.
- Measure π^+ range and energy in target and range stack.
- Stop π^+ in range stack.
- Observe $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ in range stack.
- Veto photons, charged tracks.

ORKA sensitivity Improvements



Expect ×100 sensitivity with respect to BNLexperiment ×10 from the beam and ×10 from the detector.

- 600 MeV/c K^+ beam.
- More finely segmented Range Stack.
- Longer barrel elements (Drift Chamber, Range Stack and Barrel Veto) .
- Increase thickness of Photon Barrel Veto (17.3 r.l. → 23 r.l.).
- ......

Requirements for ORKA

- π^o rejection > 10^6-10^7 ⇨ γ inefficiency < 10^{-3}-10^{-4} above 20 MeV and for impinging angles down to 20°.
  Desirable sensitivity down to few MeV (see next slides).
- Depth > 20 $X_{o.}$
- Accidentals rate: 0.011/MHz (in order to keep the same rate of accidentals as in E949).
- Desirable: γ/n identification.
- Max decay time for scintillator: 8 nsec (to keep the accidentals down).
- Energy resolution: 10-15% @ 200 MeV (from E949), but needs further studies.

ORKA Critical Experimental Issue

- Proposed Photon Veto based on Shashlik calorimeter
  155 interleaved layers of 0.8 mm lead and 1.6 mm scintillator.
  23 X_0 depth.
  - About 2/3 of energy lost in Pb absorber
  - Need to set threshold at 1pe
  - No energy measurement
- Estimated accidental losses based on E949:

$$\mathcal{S} = e^{\lambda(R_{\mathrm{ORKA}} - R_{\mathrm{E949}})}$$

- Using: λ = -0.345/MHz R_{ORKA}= 26.2 MHz R_{E949}=8.4MHz

$$\mathcal{S} = 0.54 \text{ with respect to E949}$$

Forget about expected sensitivity

Needed dedicated simulations to fully understand and optimized the detector

ORKA Critical Experimental Issue

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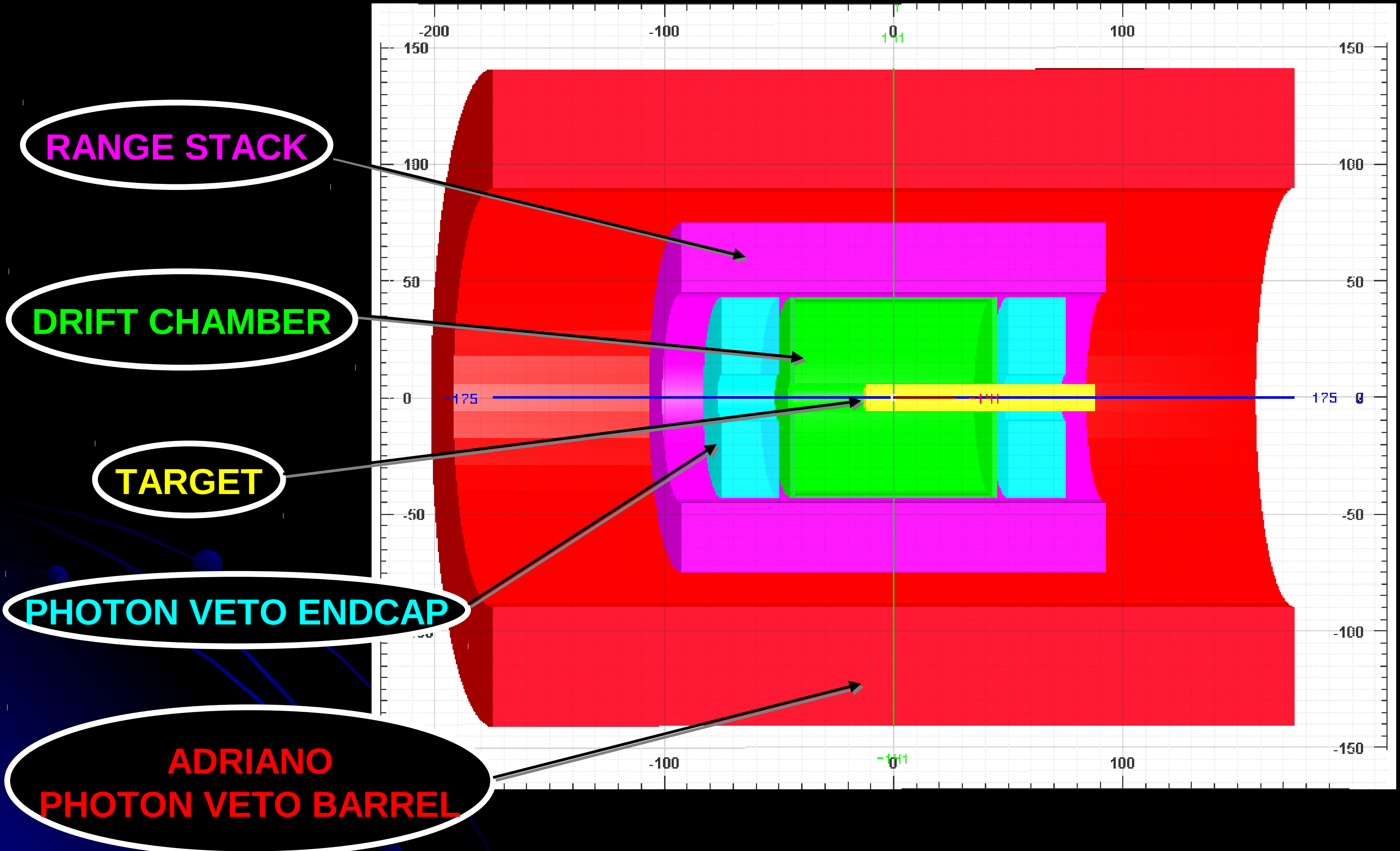
Needed dedicated simulations to fully understand and optimized the detector

ILCroot: root Infrastructure for Large Collider

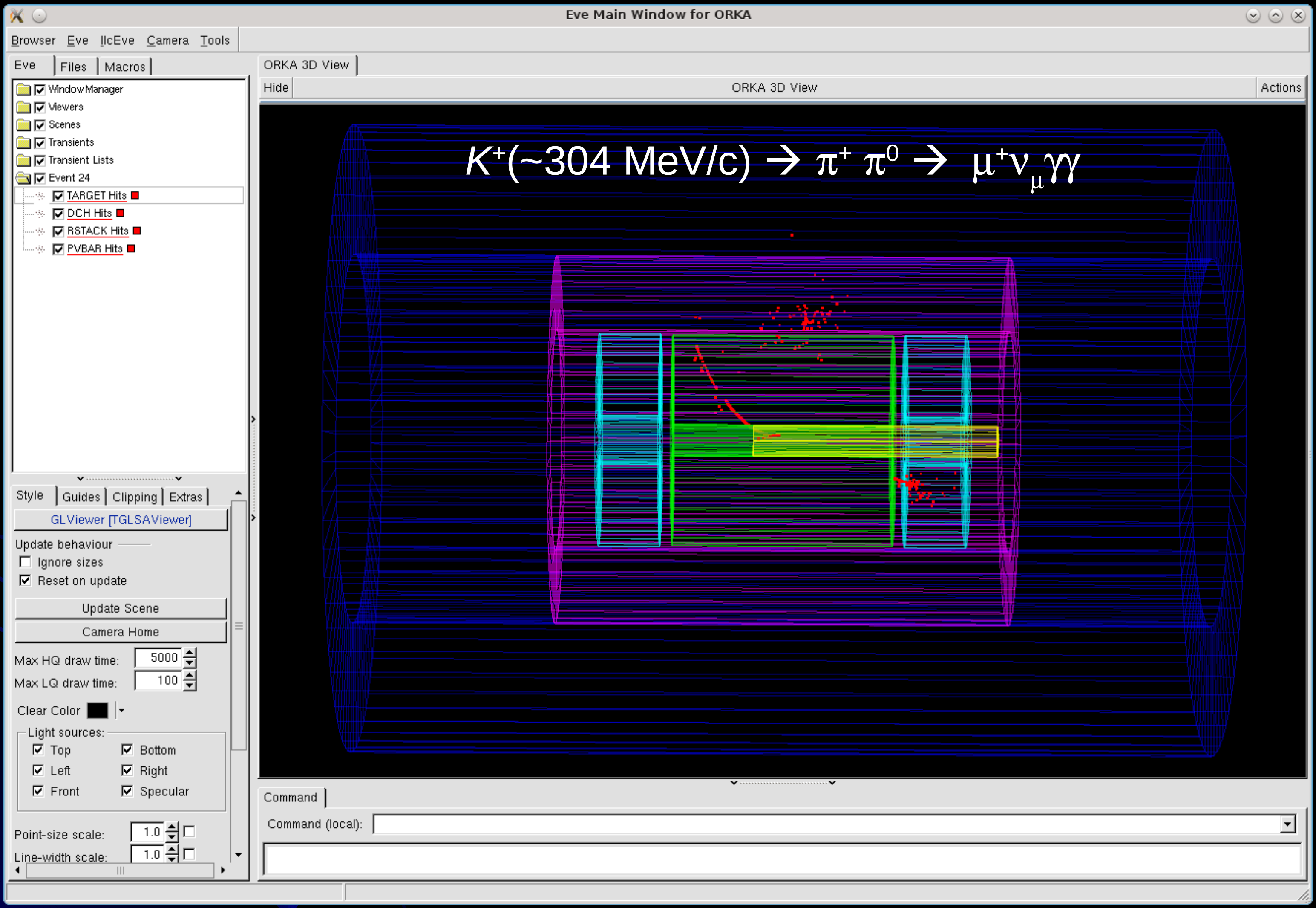
- **CERN** architecture (based on Alice's Aliroot).
- Six MDC have proven robustness, reliability and portability.
- Uses **ROOT** as infrastructure.
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc.).
  - Extremely large community of users/developers.
  - Growing number of experiments/projects have adopted IlcRoot: Opera, CMB, Panda, ILC 4th Concept, Muon Collider, ORKA
- Include **interfaces** to read external event generator outputs (Pythia, Whizard) and MARS (for the Muon Collider background).
- Virtual Geometry Modeler (VGM) for geometry .
- **Virtual Montecarlo** allows to use several MonteCarlo (Geant3, Geant4, Fluka) The user can select at run time the MonteCarlo to perform the simulations without changing any line of the code.
- **Single framework**, from generation to reconstruction through simulation. Don't forget analysis!!!
- IlcRoot successfully adopted for the ILC and actually used for the MuC detector studies for Snowmass.

  (**LoI** studies for the ILC (4Th Concept) completed based on IlcRoot).

ORKA Detector in ILCroot

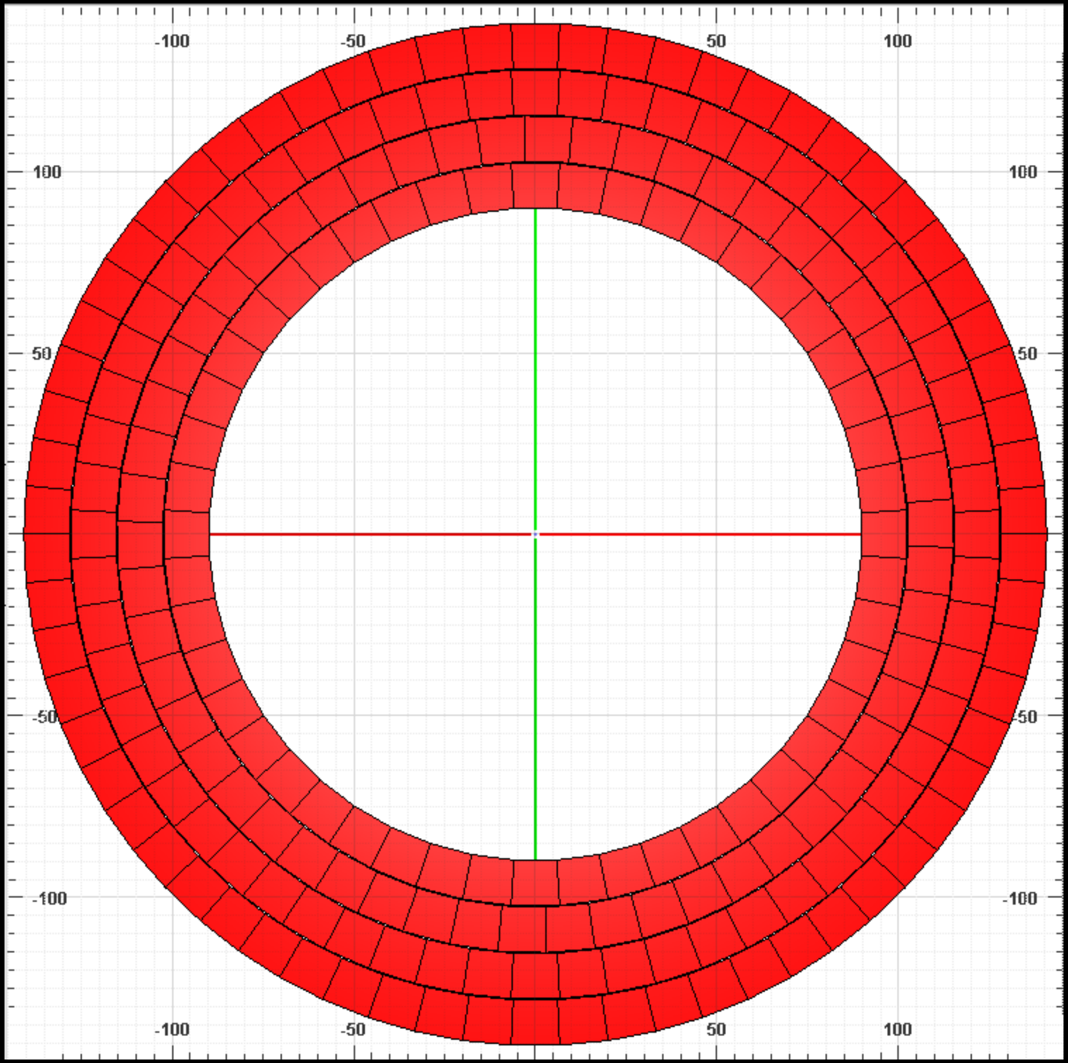


IlcRoot Event Display

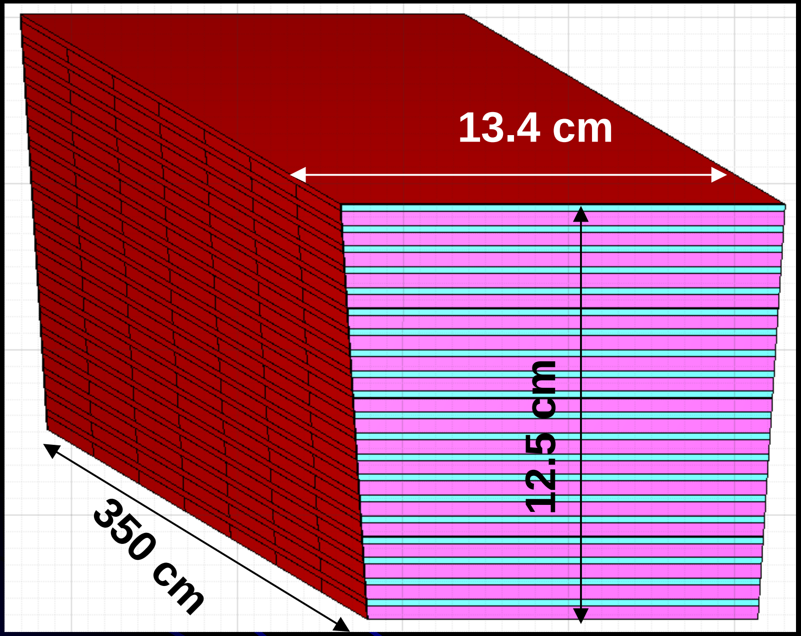


ADRIANO Photon Veto Barrel Geometry

- PV Barrel divided into 4 layers 12.5 cm thick.
- Z = 350 cm.
- $R_{in} \simeq 89.7$ cm.
- $R_{out} \simeq 140.8$ cm.
- Each layer subdivided in cells with similar transverse section.
- Cells per layer {48, 54, 60, 66}
- Cells staggered to avoid aligned cracks.
- Open space between layers filled with Plexiglas



ADRIANO Photon Veto Barrel Geometry



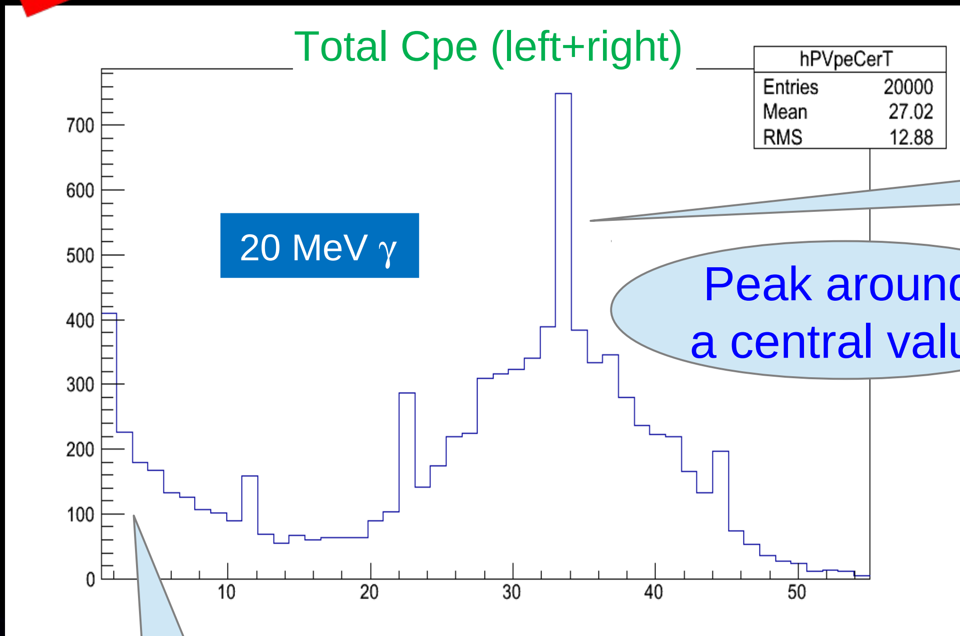
- Elementary cell has trapezoidal shape:
- Major base = 13.4 cm.
- Thickness = 12.5 cm.
- 20+20 alternated tiles optically de-coupled lead-glass (4.2 mm thick) scintillator (2.0 mm thick)
  + glue (25 μm thick).
- lead-glass made in 7 glued segments (50 cm long) along z.
- Photons collected in lead-glass and scintillator by distinct WLS.
- Each cell divided into 3x2x2 channels/side (ϕ, R, Cer/Sci). Readout on both sides.

Advantages of ADRIANO For ORKA

1. Energy from Cerenkov signal is narrower and picked also at low energy.
2. Integrally active detector has lower inefficiency than sampling calorimeters.
3. Left-right reading of Cerenkov signal provide z-component measurement (important for π^0 reconstruction).
4. PID from S vs C helps in reducing accidentals from neutrons.

Preliminary

Čerenkov signal is narrower



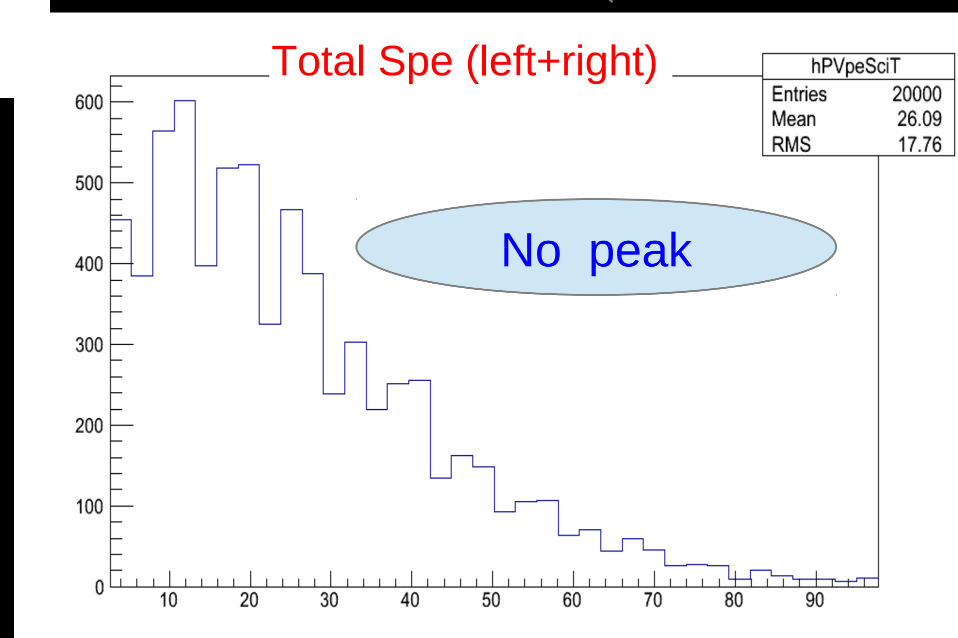
γ interacting in ADRIANO

Peak around
a central value

Same situation as Shashlik

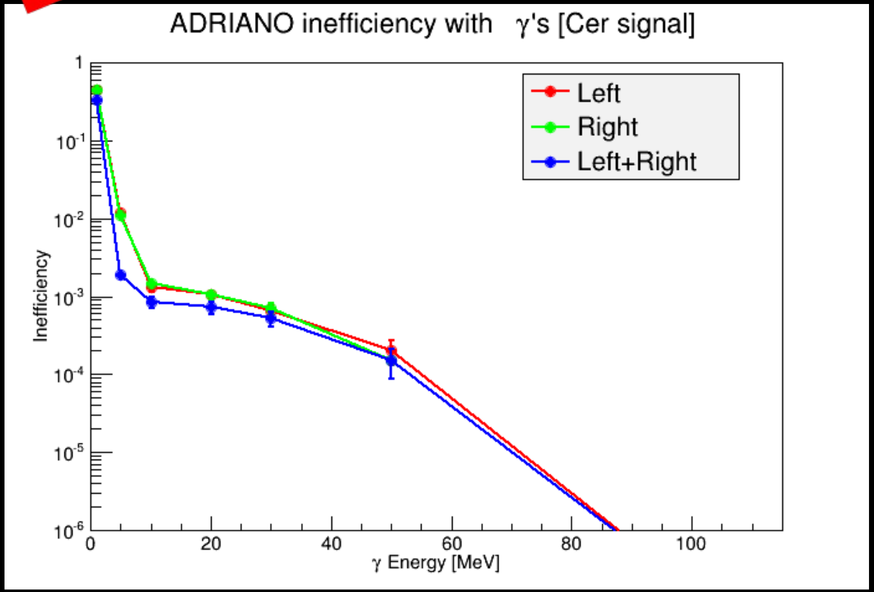
A binomial component
appears at low energies
in the scintillating signal

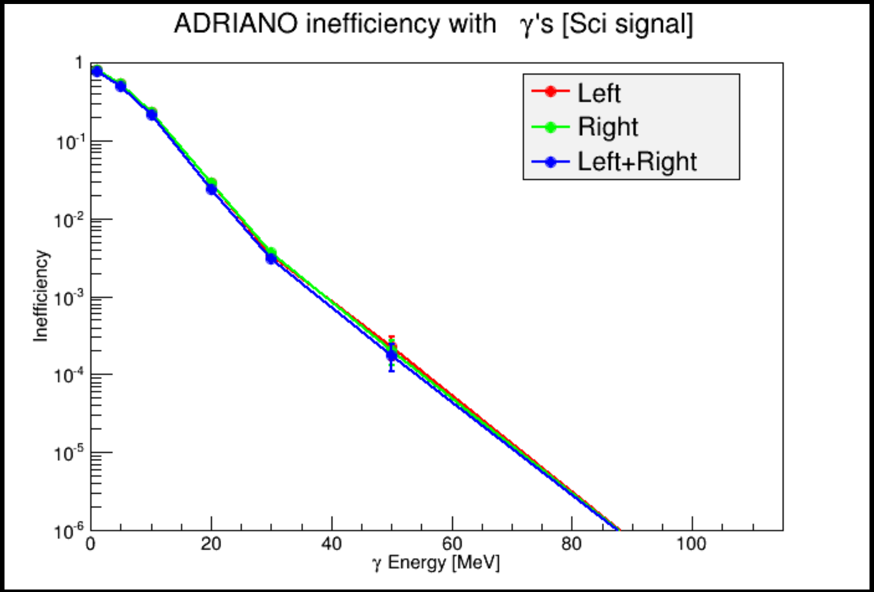
γ interacting before ADRIANO

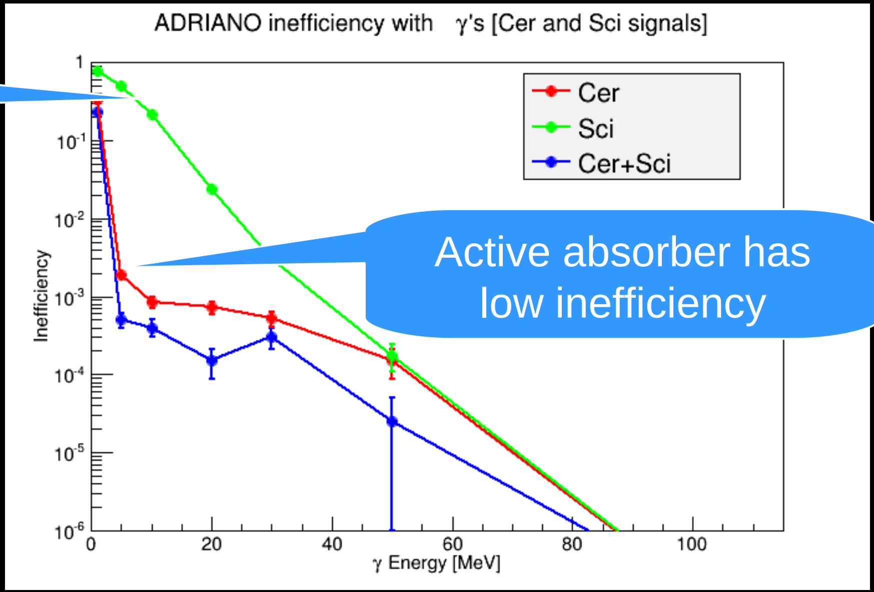


Integrally active detector has lower inefficiency

Preliminary







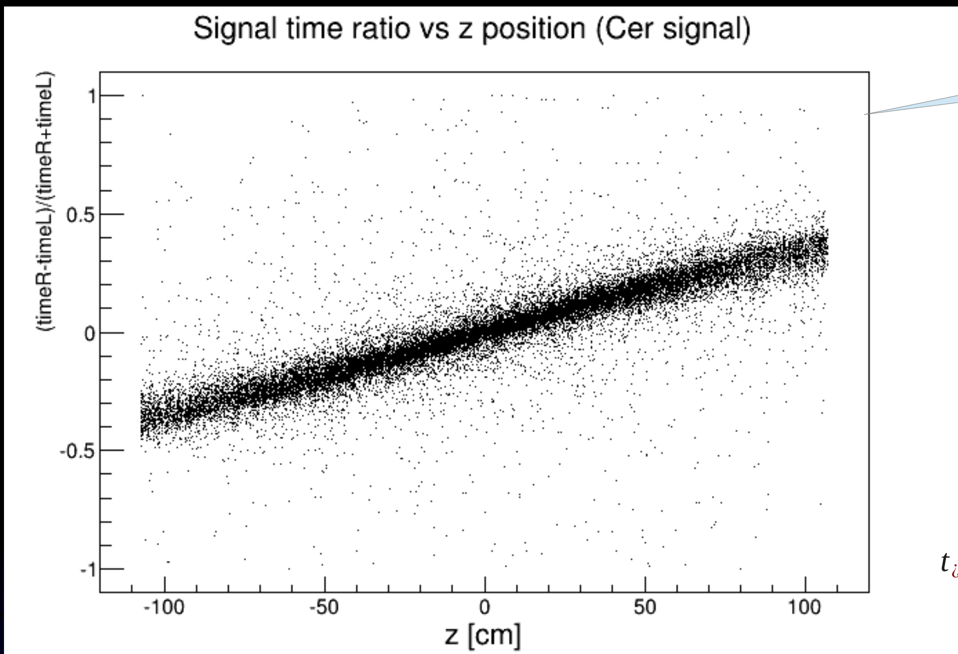
Scintillating signal suffers at low energy from sampling mechanism

Active absorber has low inefficiency

Integrally active detector has lower inefficiency

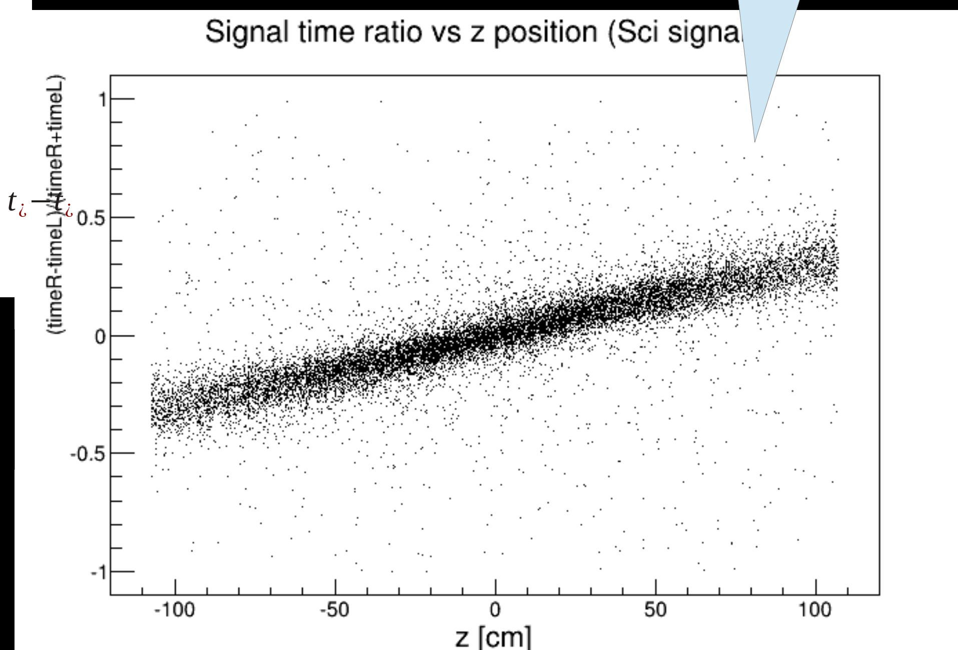
Preliminary

Left-right reading of Cerenkov signal provide z-measurement



Lead glass

Scintillator



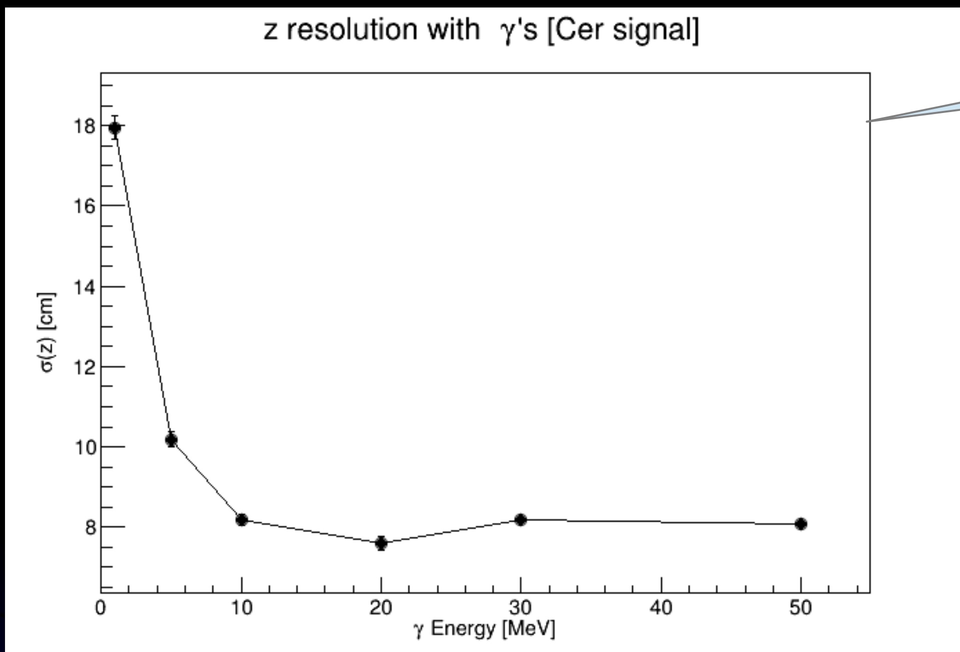
Time difference from the readout both sides for z measurement

$$z \propto \frac{t_R - t_L}{t_R + t_L}$$

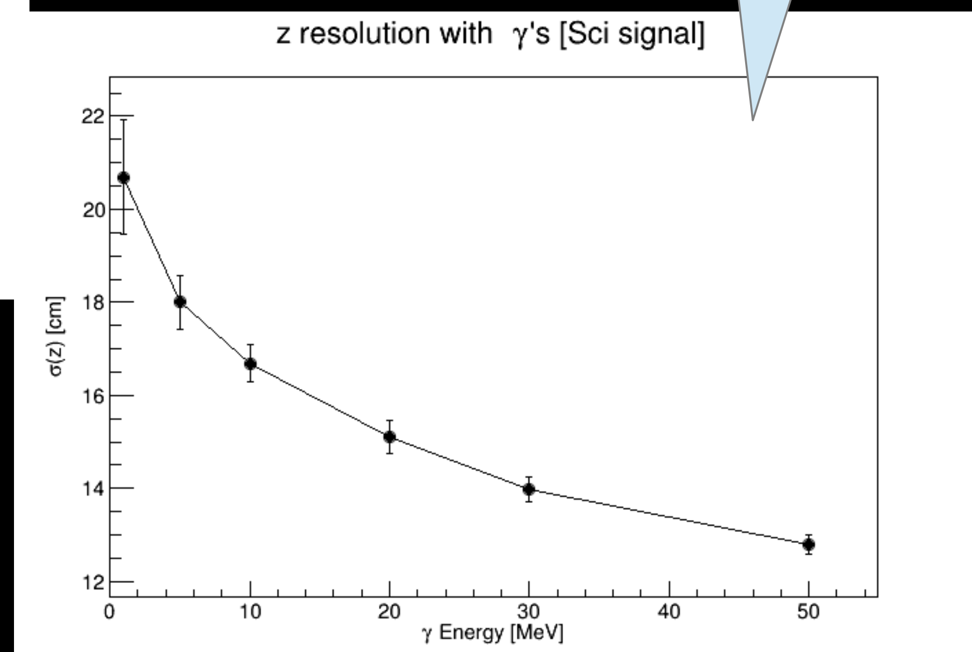
Preliminary

Left-right reading of Cerenkov signal provide z-measurement

Lead glass



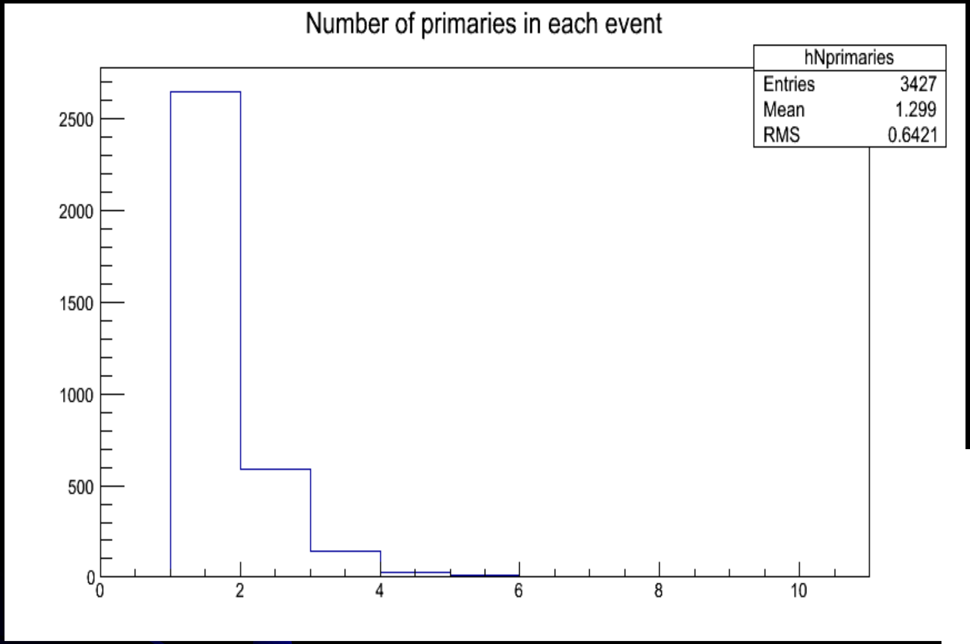
Scintillator



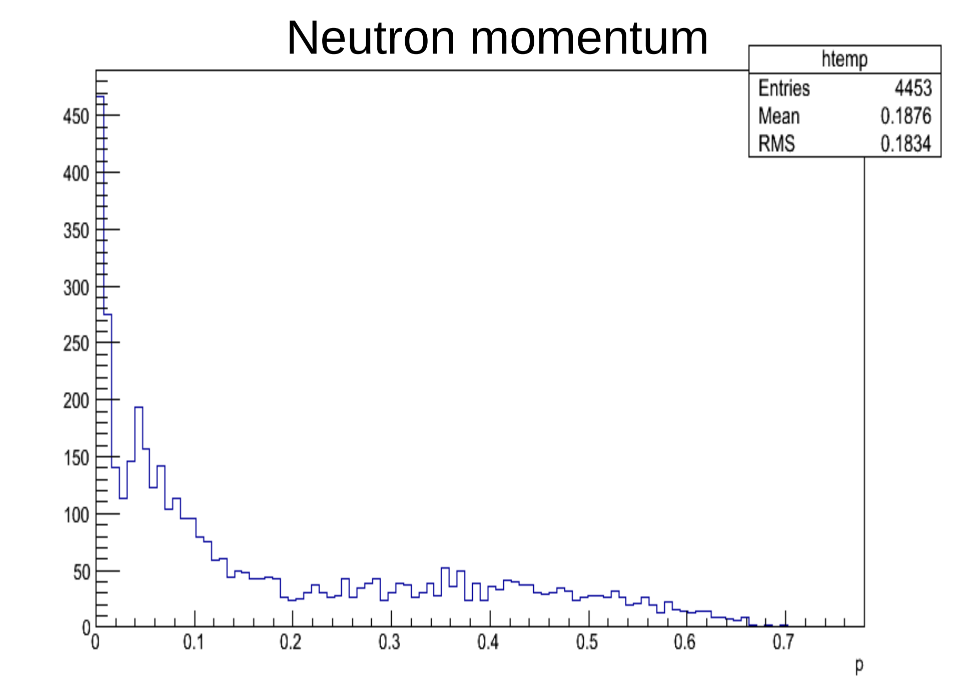
Cer time give better resolution.

Čerencov signal is promt. Only decay time from WLS.

PID from sci vs cer

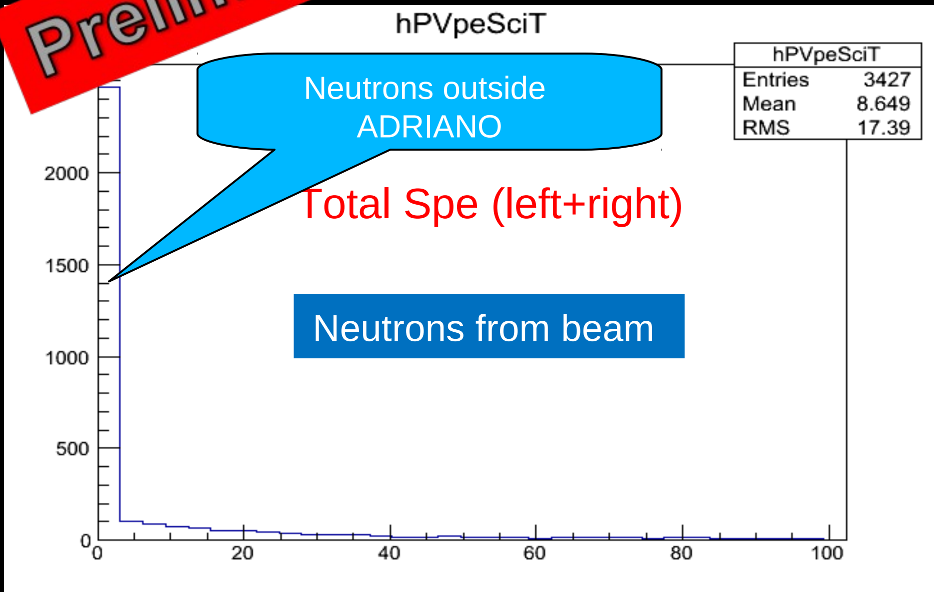


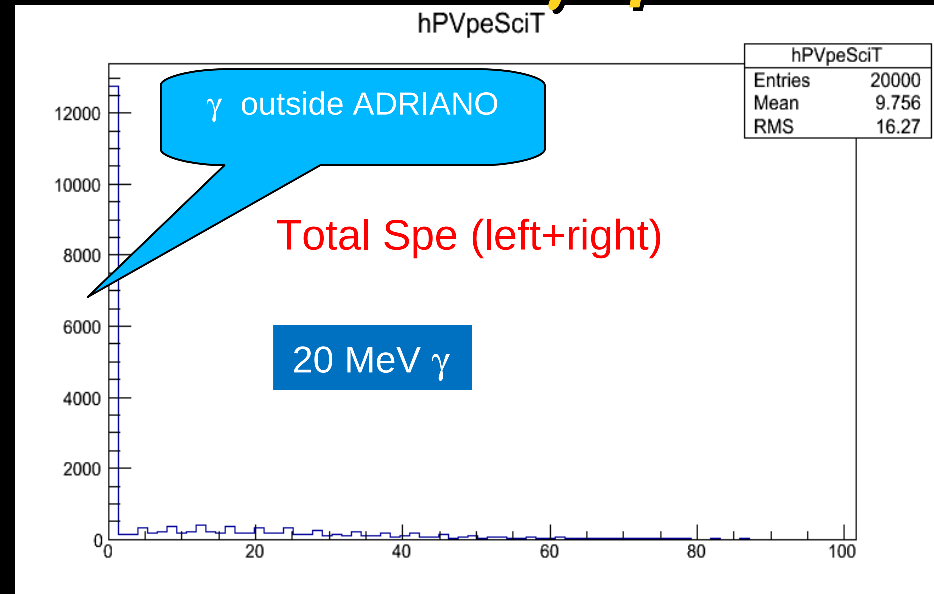
(Preliminary study by J. Jensen for Kaon beam)



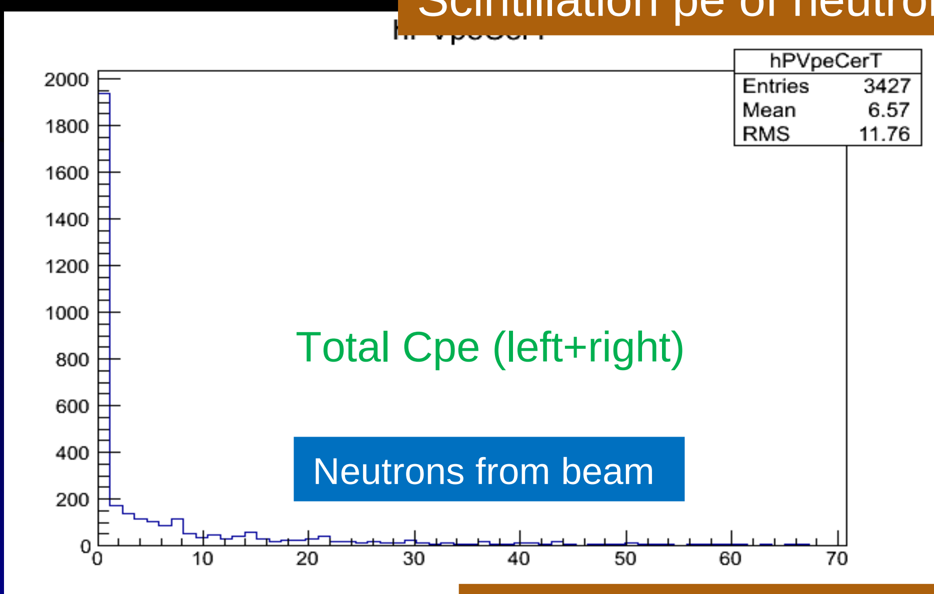
Preliminary

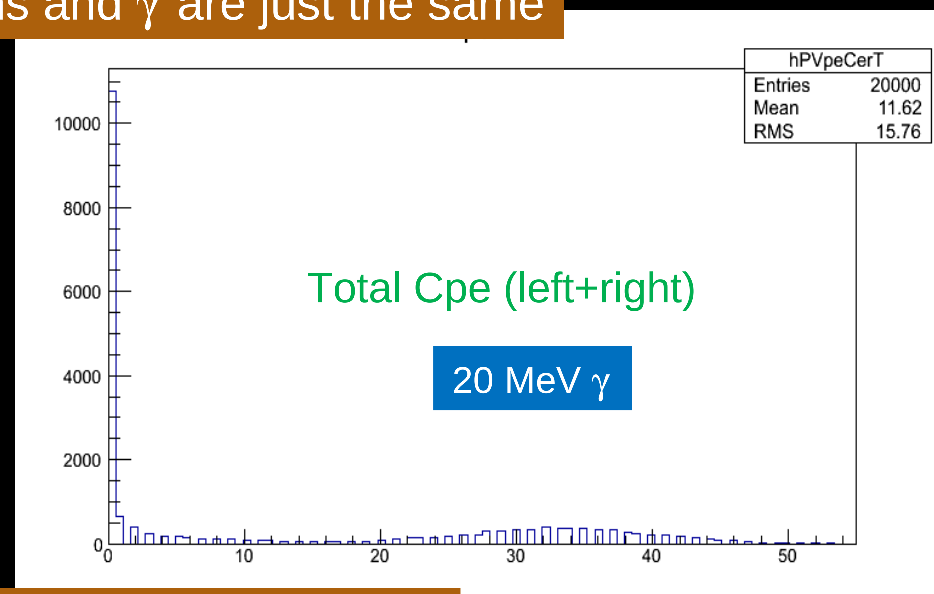
Neutron effects in ADRIANO vs 20 MeV γ: pe/evt





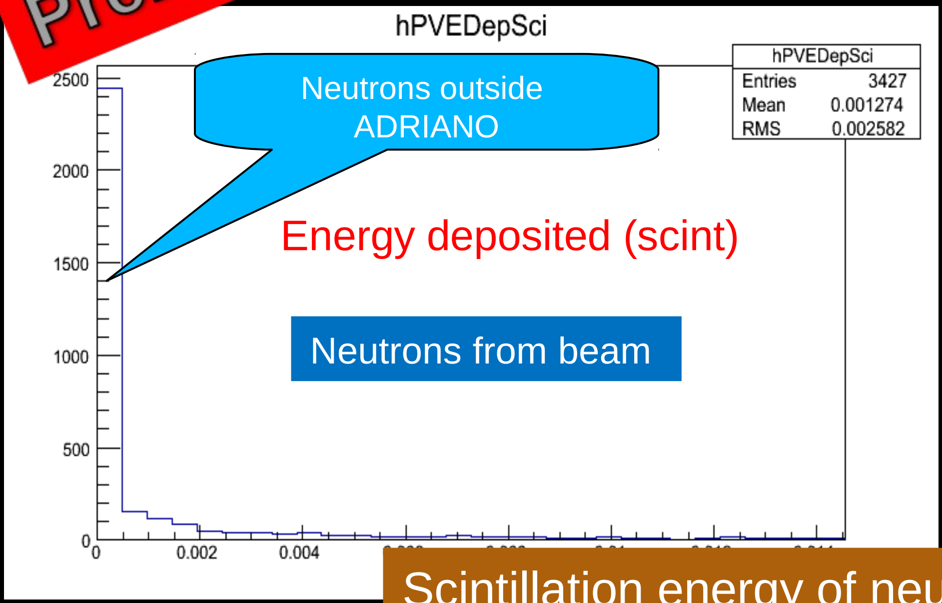
Scintillation pe of neutrons and γ are just the same

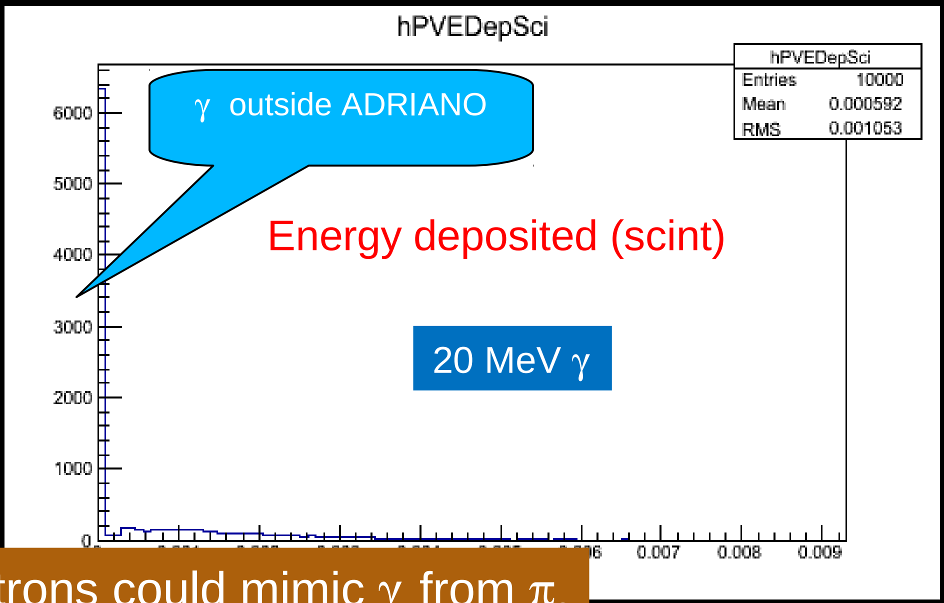




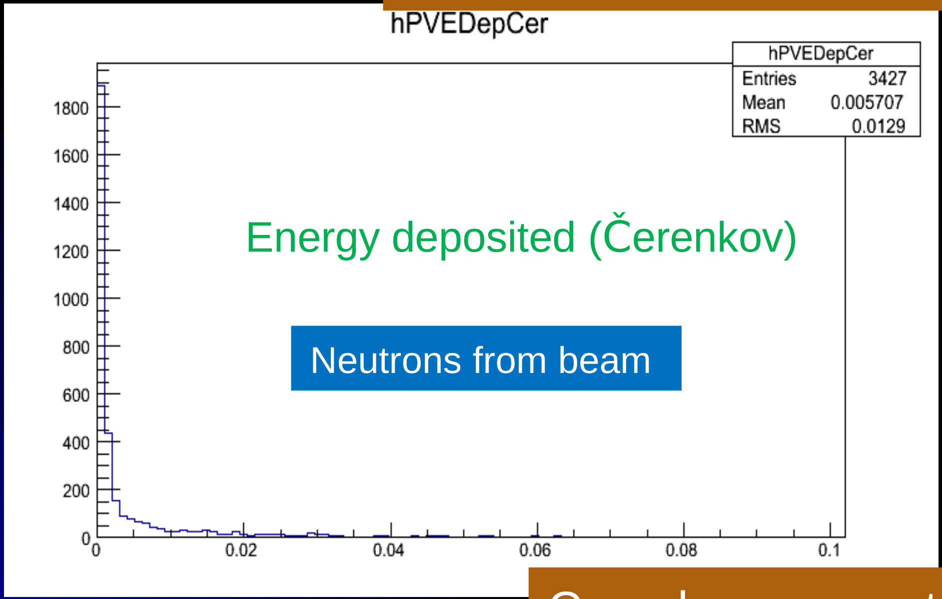
Cerenkov pe distributions are very different

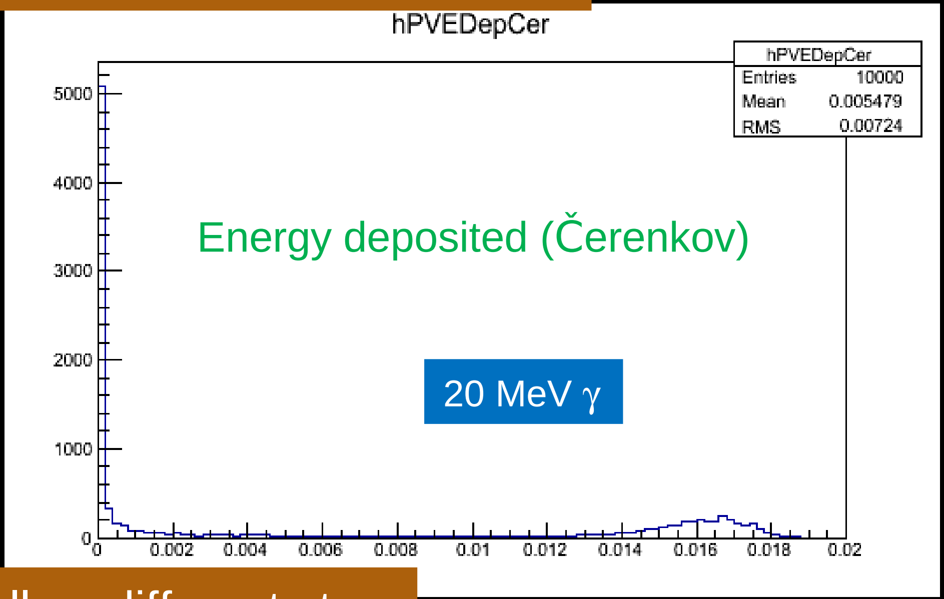
Preliminary ...n effects in ADRIANO vs 20 MeV γ : Edep/evt





Scintillation energy of neutrons could mimic γ from π_o

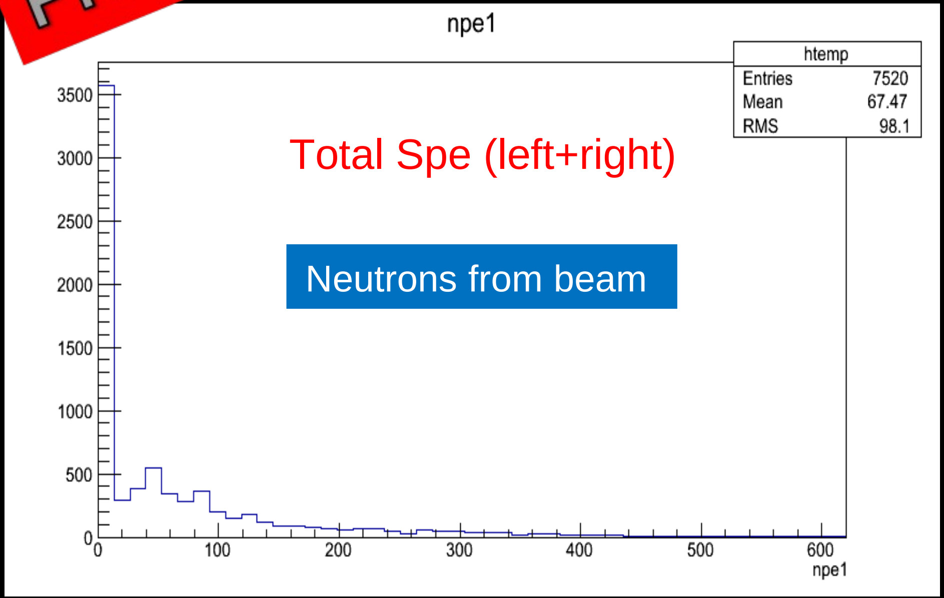


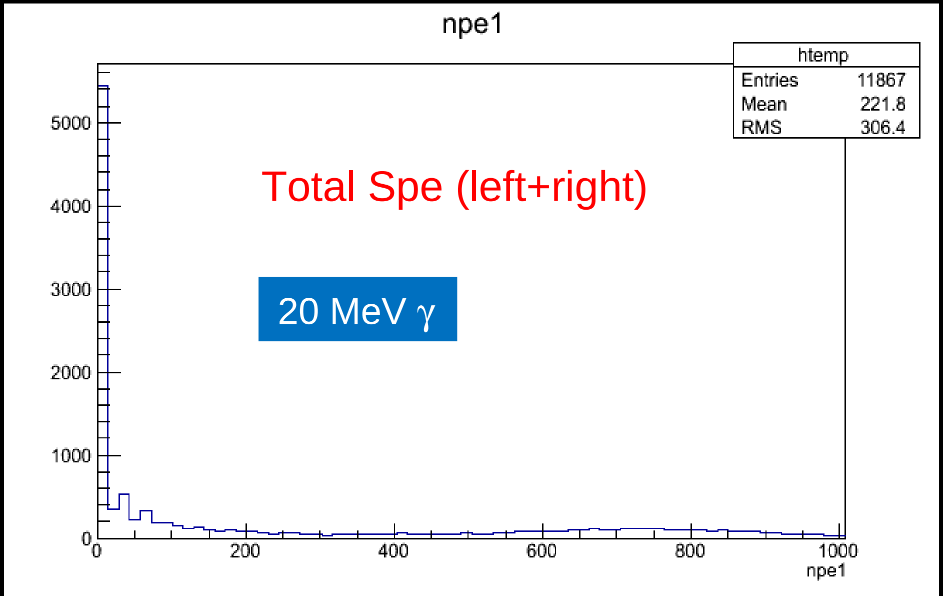


Cerenkov energy tells a different story

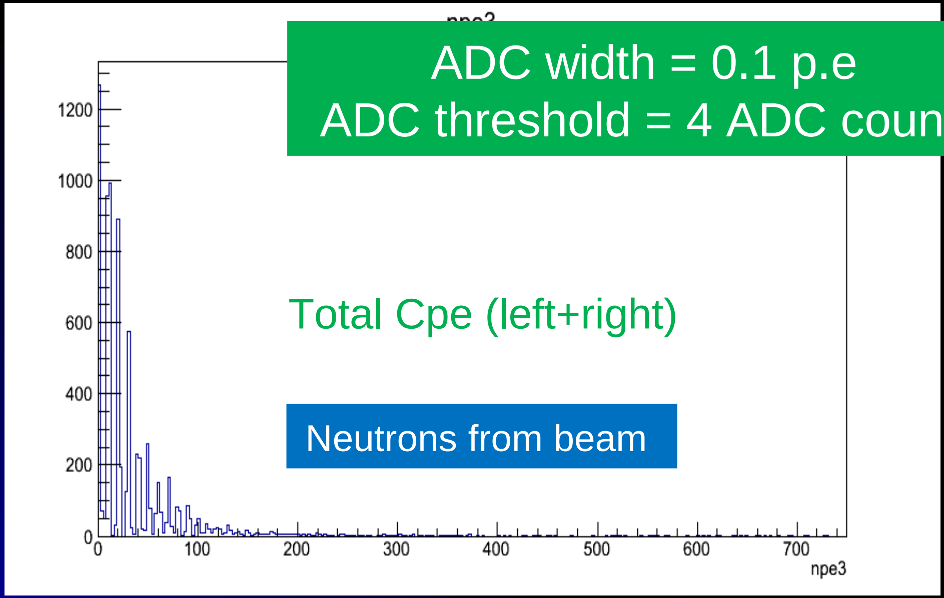
Neutron effects in ADRIANO vs 20 MeV γ: ADC count

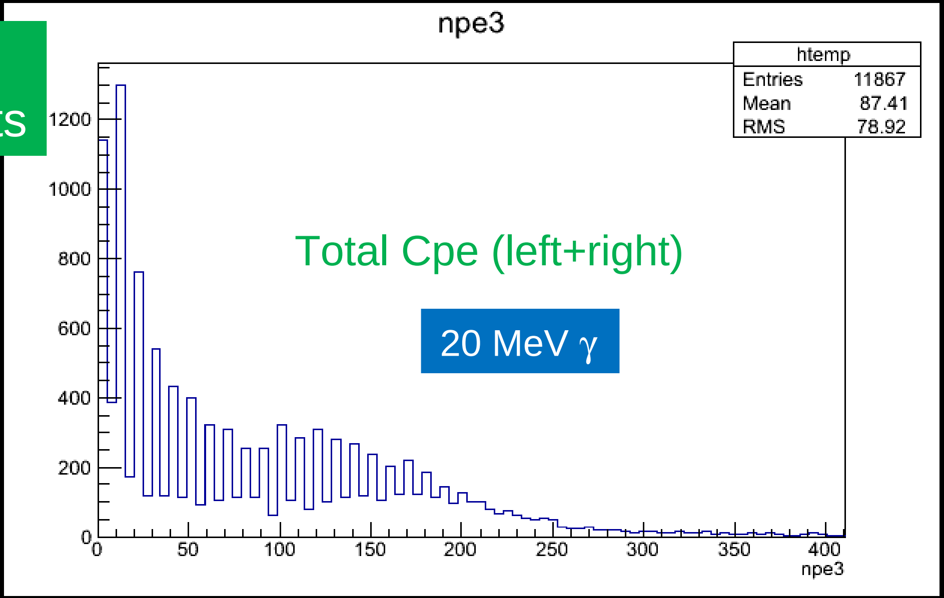
Preliminary





ADC width = 0.1 p.e
ADC threshold = 4 ADC counts





Summary

- Dual-readout technique improves the energy resolution of a hadronic calorimeter.
- It is one of the two approaches for a calorimeter at future Lepton Colliders.
- ADRIANO technique overcomes limits of sampling calorimeters.
- Intense R&D ongoing at Fermilab and Italy.
- Proposed a modified version of ADRIANO calorimeter for ORKA photon veto Barrel.
- Two options under study:

A) ADRIANO in dual-readout mode

B) ADRIANO in single readout mode

- Intense simulation activity in progress using IlcRoot framework.
- Future test beams at FNAL and University of Naples already planned.
- Approved project between University of Naples and INFN to build a “neutron line” at an extisting TANDEM facility with tagged neutrons from nuclear reaction in 2MeV-12 MeV range ($D+D \rightarrow He^3 + n$).

Backup Slides

ORKA Motivation

Access to NP at and beyond LHC mass scale.

New Physics found at the LCH	New Physics NOT found at the LCH
Precision flavor-physics experiments needed to help sort out the flavor- and CP-violating couplings of the NP.	Precision flavor-physics experiments needed to access to mass scales beyond the reach of the LHC (through virtual effects).

Special processes to probe NP

$\mu \to e\gamma$, $\mu \to e$ conversion, $\pi^+(K^+) \to e^+\nu$

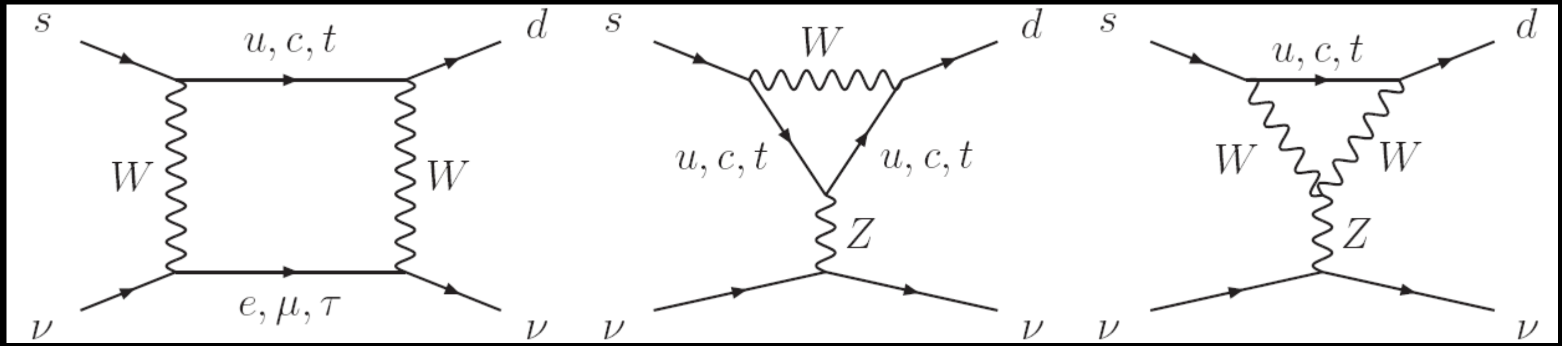
$K^+ \to \pi^+\nu\nu$, $K^0_L \to \pi^0\nu\nu$

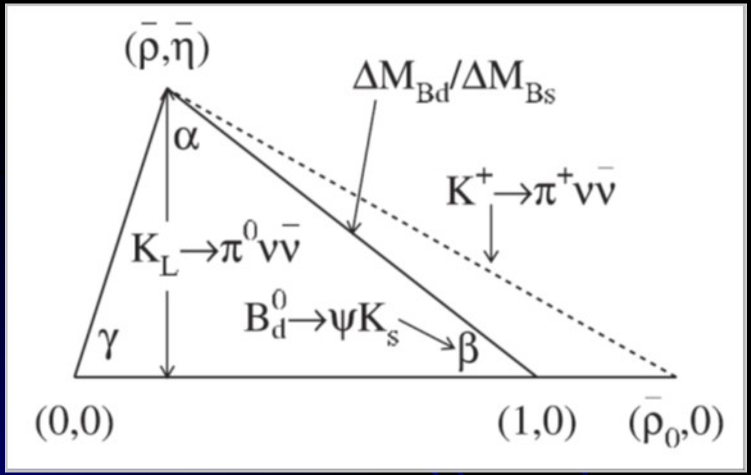
$b \to s\gamma$, $B \to \mu\mu$, $(\tau \to \mu\gamma)$

Special status: small SM uncertainty and large NP reach.

$K^+ \to \pi^+ \nu\nu$ in the Standard Model

The $K^+ \to \pi^+ \nu\nu$ *decays are the most precisely predicted FCNC decays with quarks*





Brod, Gorbahn, Stamou PR **D83**, 034030 (2011)

- A single effective operator $\boxed{(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)}$
- Dominated by top quark (charm significant, but controlled)
- Hadronic matrix element shared with Ke3
- Uncertainty from CKM elements (*will improve*)
- **Remains clean in most New Physics models**

(unlike many other observables)

$$B_{SM}(K^+ \to \pi^+ \nu\bar\nu) = (7.8 \pm 0.8) \text{ x } 10^{-11}$$

Photon Veto or Calorimeter

It depends on the process!

Process	Current	ORKA
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$
$K^+ \to \mu^+ \nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$
$K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$
$K^+ \to \pi^+ \gamma\gamma$	293 events	200,000 events
$\Gamma(Ke2)/\Gamma(K\mu 2)$	$\pm 0.5\%$	$\pm 0.1\%$
$\pi^0 \to \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 5 \times 10^{-8}$ to $< 4 \times 10^{-9}$
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$

Photon Veto or Calorimeter

Photon veto required here

Process	Current	ORKA
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events
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Photon Veto or Calorimeter

Energy measurement required here

Process	Current	ORKA
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$
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$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$

Technologies For Barrel

Shashlyk

Pro

Cheap

Well established technology

Extensive test beam

- Cons
  - Sampling fluctuations
  - Inadequate for E_{γ}<50 MeV see KOPIO R&D
  - Large inefficiency for low energy photon

ADRIANO in dual-readout mode

- Pro
  - Integrally active calorimeter
  - Higher detection efficiency
  - S vs C provides PID

- Cons
  - More expensive
  - Novel technology
  - Tested only at high energy (500 MeV)

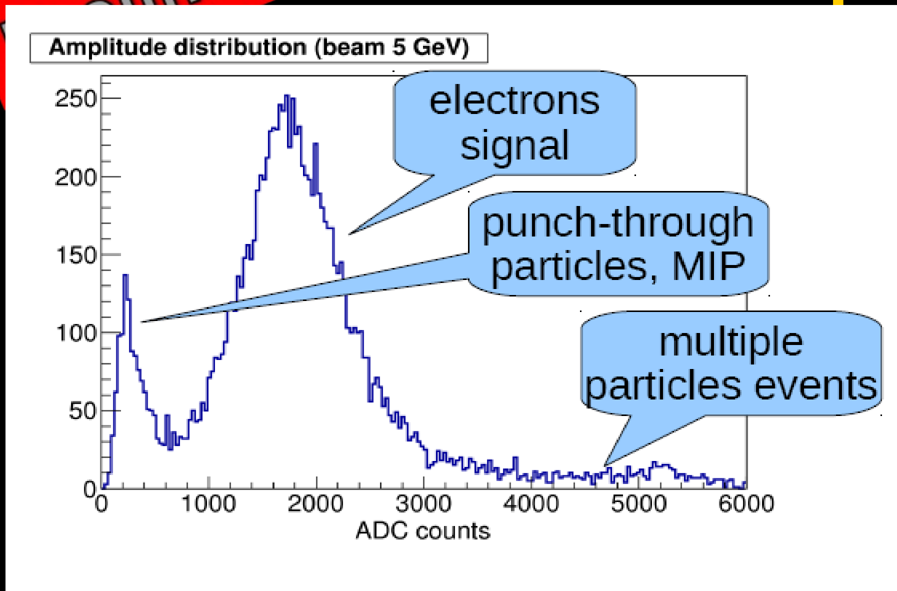
ADRIANO in single readout mode

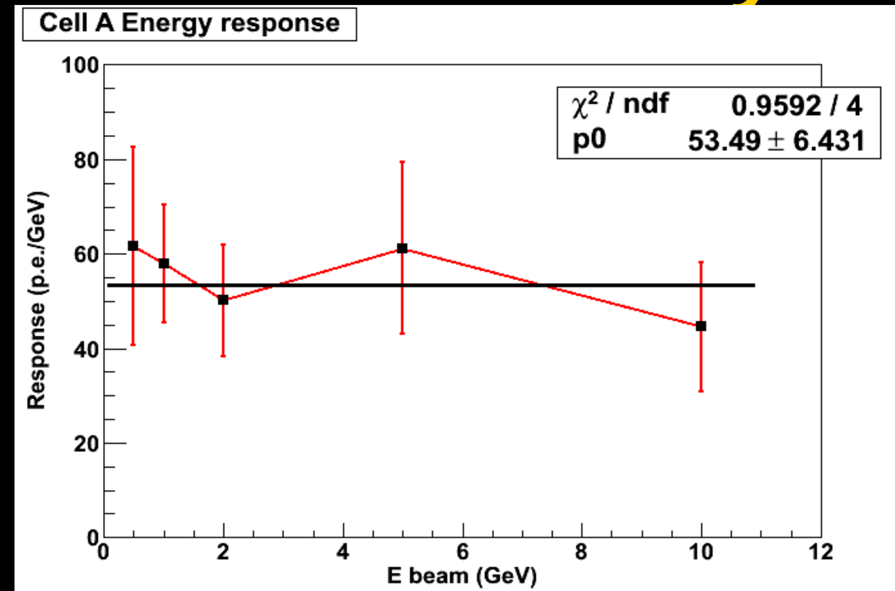
- Pro
  - Integrally active calorimeter
  - Highest detection efficiency

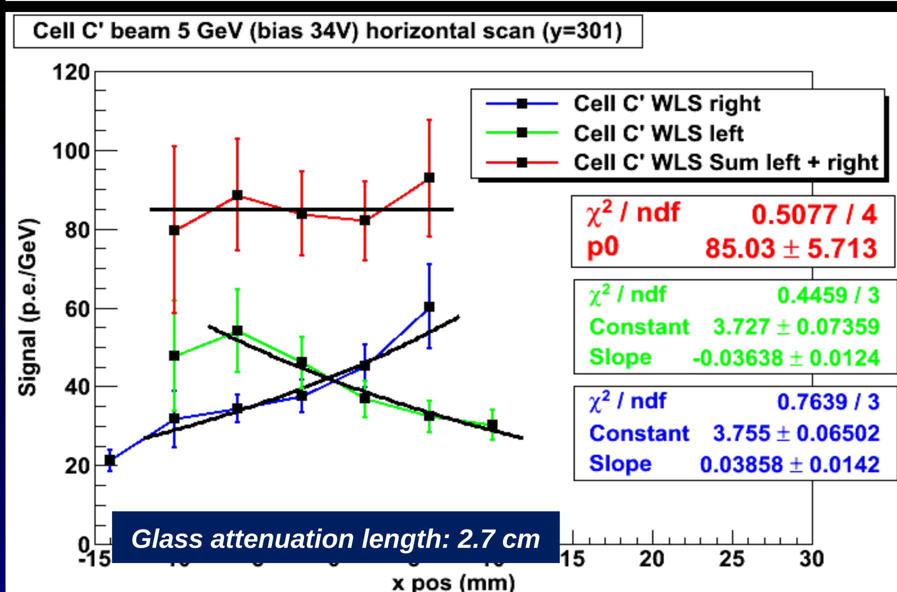
- Cons
  - Also expensive
  - Untested technology
  - No PID

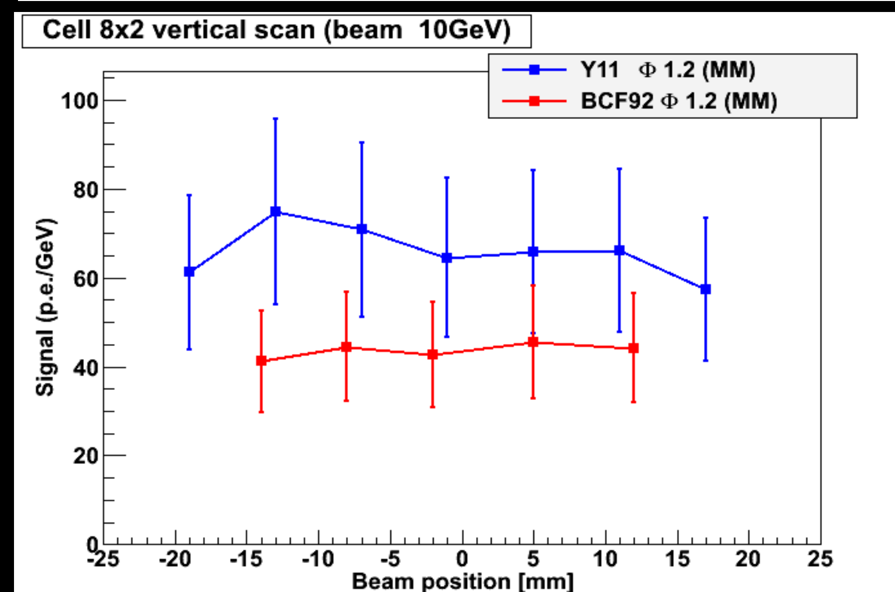
Detector Response Uniformity

Preliminary

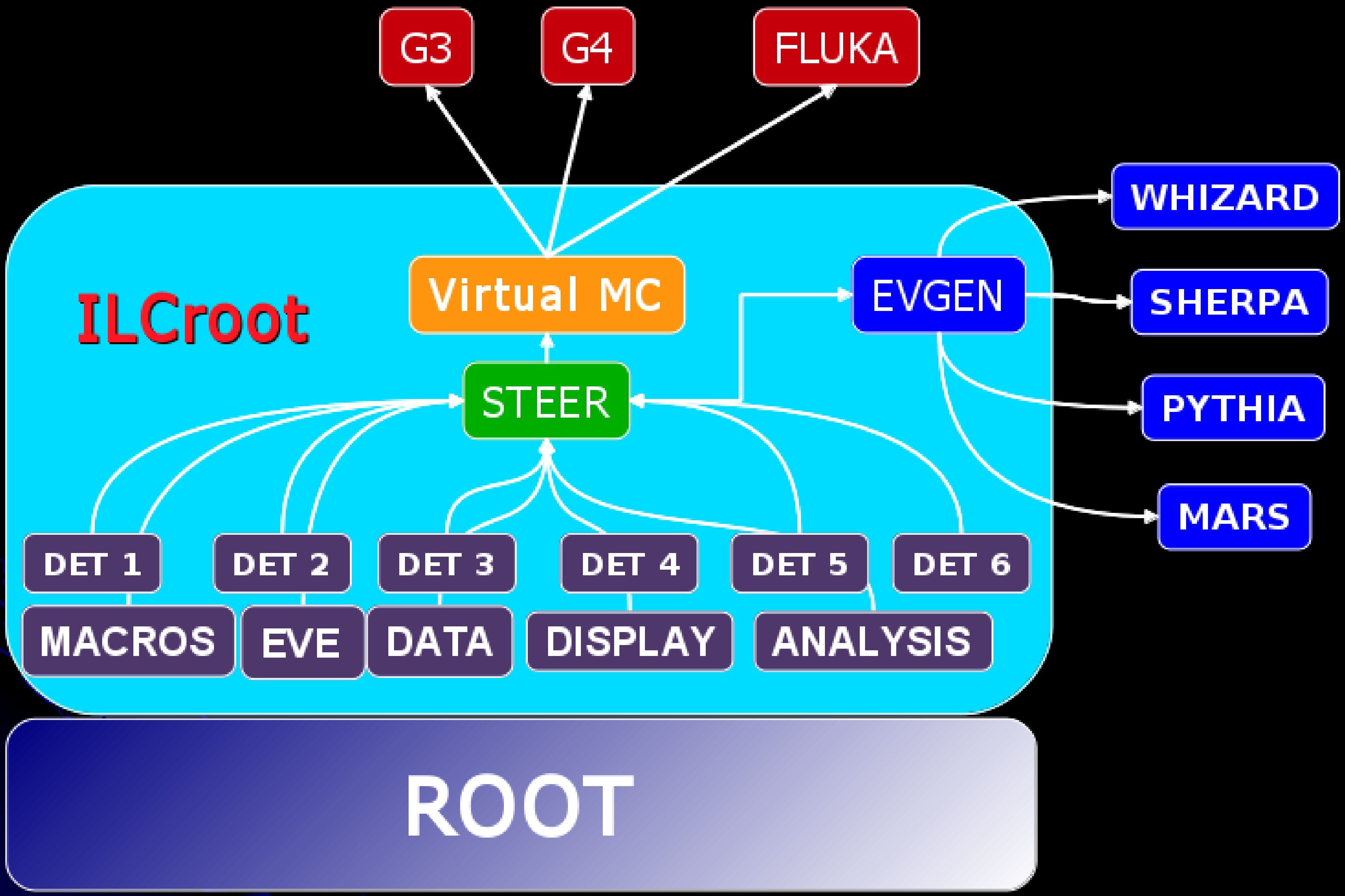




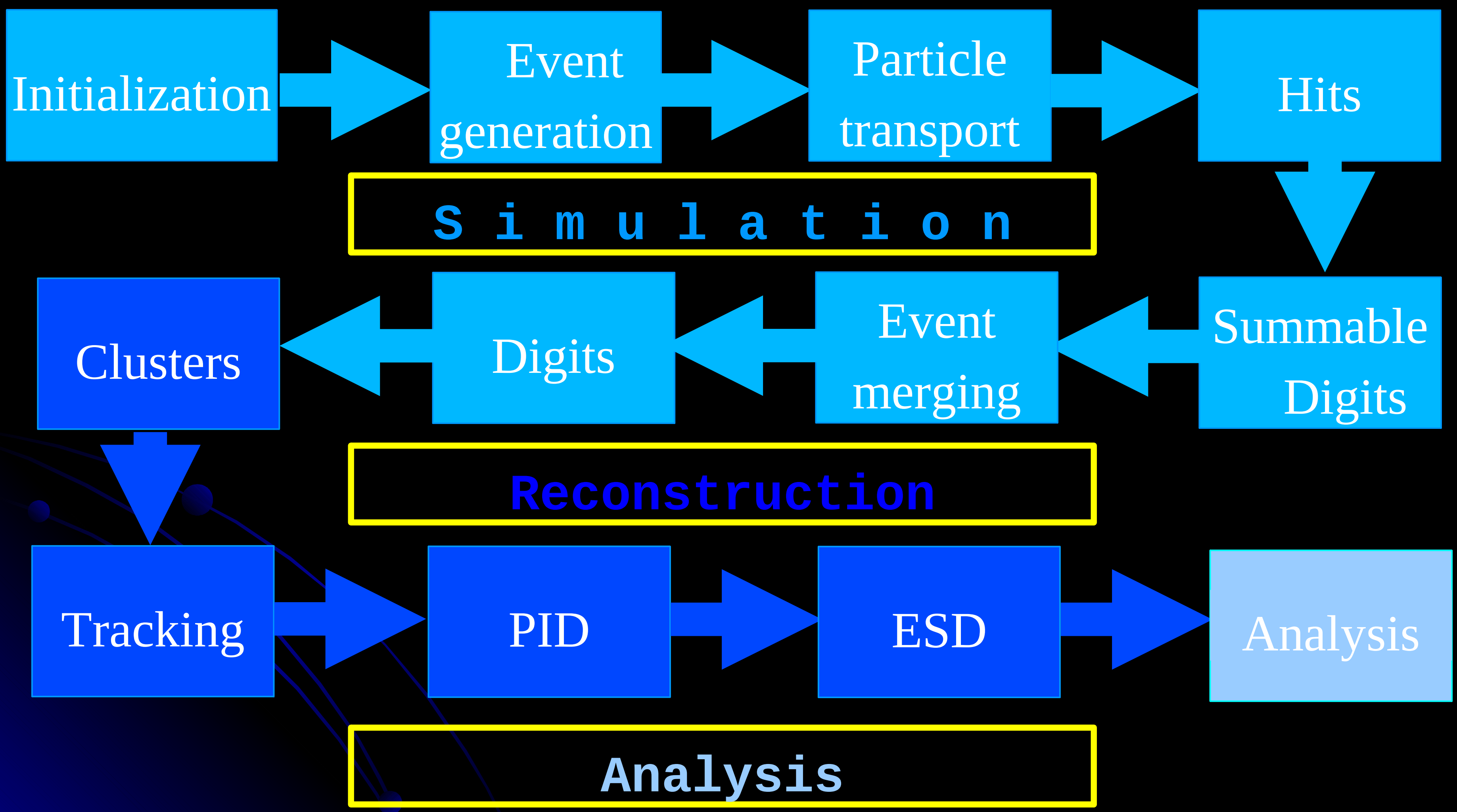




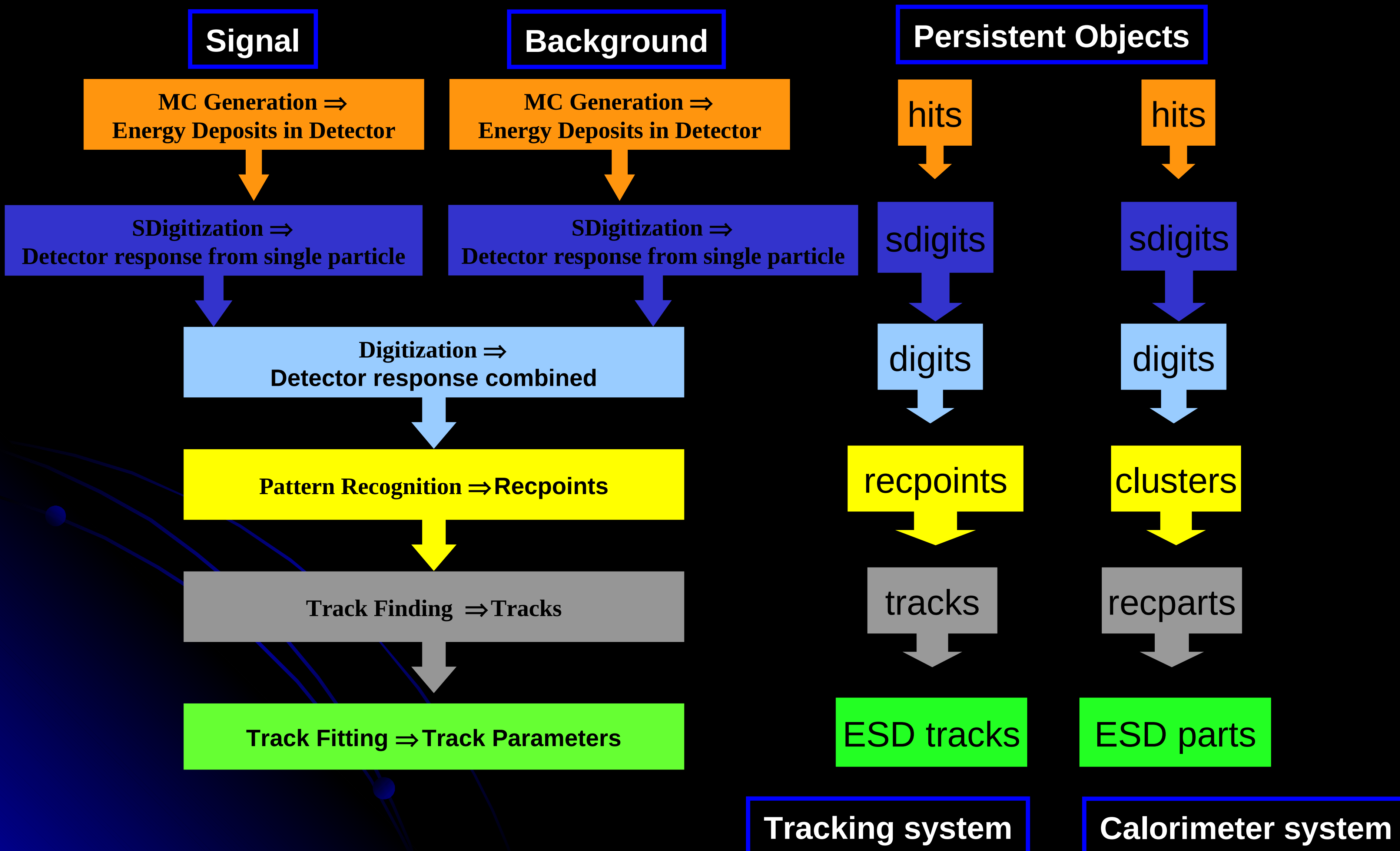
ILCroot Framework



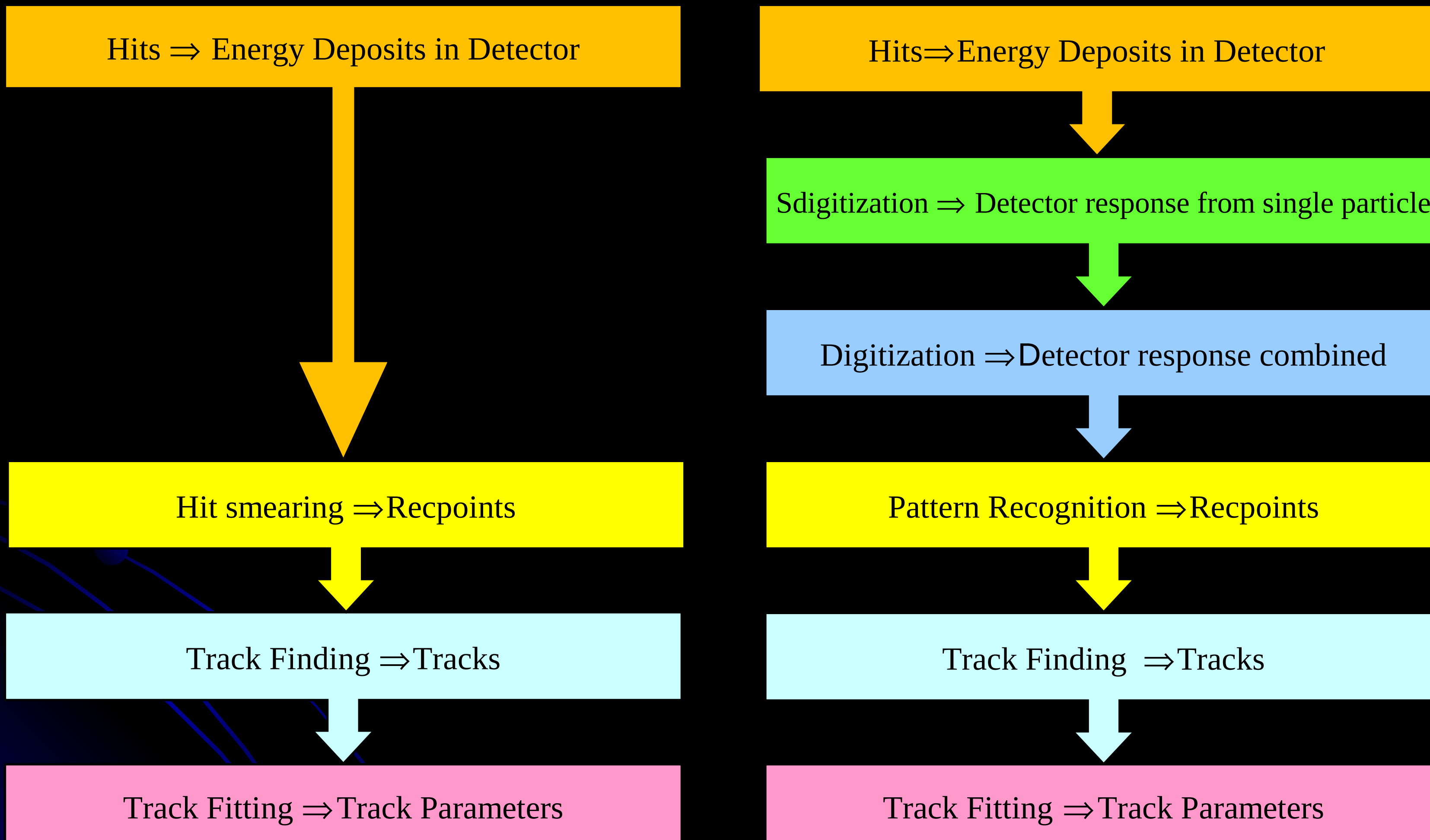
ILCroot Flow Control



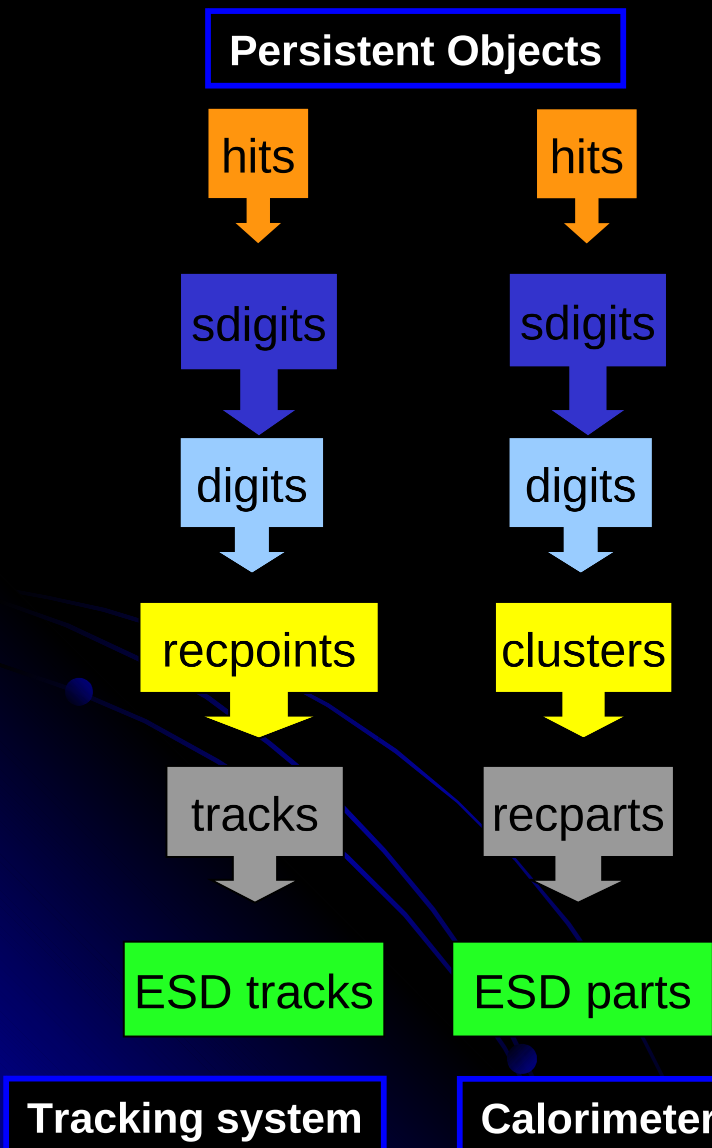
ILCroot Simulation steps



ILCroot Fast vs Full Simulation



Detector Simulation Status



Target	DCH	RS	PVBAR	PVEC
X	X	X	X	X
X	X	X	X	X
X	X	X	X	X
X	X		X	
X	X		X	
X	X		X	

ADRIANO: simulation chain

Hits:
Pacticles interaction with media.
Relevant output: **photons**

SDigits:
Is the ideal contribution to Digits originate by each Hit.
Is ideal detector response without Front End Electronics effects.
Relevant output: **p.e.**

Digits:
is the sum of all SDigits belonging to the same electronics channel.
it takes into account Front End Electronics.
Relevant output: **ADC counts**

Hits production in ADRIANO

- **Scintillating component.**
  - Select charged particles.
  - Get energy deposition (dE).
  - Apply Birk's correction to dE.
  - **Apply decay time in scintillator and in WLS.**
- **Cerenkov component.**
  - Cerenkov angle evaluated via Sellmeier dispersion relation and particle beta.
  - Cerenkov photons generated with appropriate wavelength spectra in 5nm bins.

$$dN_\gamma = 2\pi L_{step}\,\alpha \sin^2(\theta_C)\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)$$

  - **Apply decay time in WLS.**
- **Both components.**
  - Calculate light-yield.
  - Hits merged within the same channel, from same primary and within 1ps time window.
- **Used parameters.**
  - Scintillator Light Yield Mean: 133 photons/MeV (take into account reflection, absorption and WLS collection efficiency).
  - DecayTime WLS: 2.4 ns
  - DecayTime scintillator: 2.4 ns

SDigits production in ADRIANO

- **Scintillating and Cerenkov component.**
  - Apply WLS attenuation length.
  - Apply WLS → SiPM collection efficiency.
  - Apply SiPM detection efficiency (PDE).
  - Apply Poisson smearing.
  - **Update time with travel time of light in WLS.**

- **Used parameters.**
  - WLS attenuation length: 450 cm.
  - WLS → SiPM collection efficiency: 90%.
  - PDE $\simeq$ 20% (depend on light wavelength).

Digits production in ADRIANO

- **Scintillating and Cerenkov component.**
  - Limit number of p.e. to total number of SiPM pixels.
  - Apply shot noise.
  - Apply Excess Noise Factor (ENF).
  - **Apply z position fluctuation (From KLOE $\propto$ 1/sqrt(E[GeV])).**
  - Apply electronic gain and convert p.e. in ADC counts.
  - **Apply electronic rise time.**
  - Remove Digits below threshold.

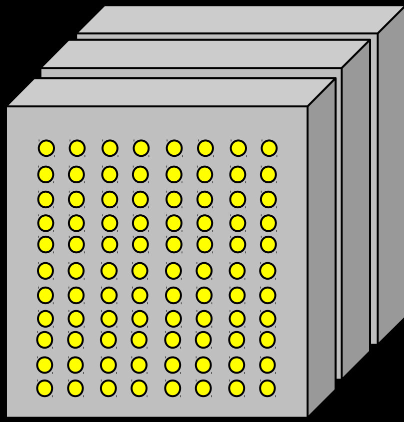
- **Used parameters.**
  - Number of SiPM pixels = 6400.
  - SiPM shot noise = 0.1 p.e.
  - ENF = 1.016.
  - Z position fluctuation = 6mm/sqrt(E[GeV]).
  - Electronic gain = 10 (can be different for Cer and Sci signal).
  - ADC width = 0.1 p.e. (can be different for Cer and Sci signal).
  - Electronic RiseTime = 0.5 ns.
  - ADC threshold = 4 ADC counts. (can be different for Cer and Sci signal).

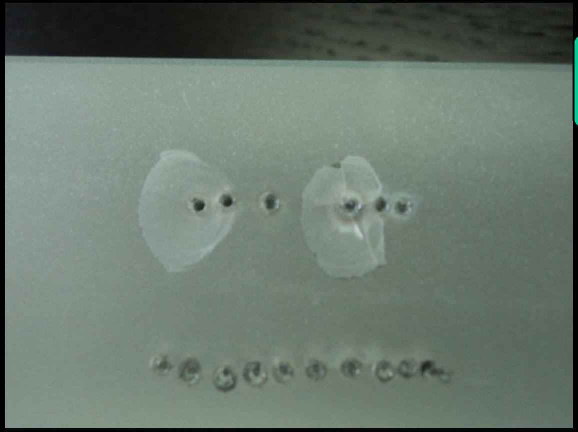
Very Intense R&D within T1015 Collaboration

- 5 test beams scheduled in 2011-2012 at FTBF
- Several cells in different configurations (40x40x250 mm^3)
- Many variants of ADRIANO
- Tested: glass, fibers, coating, optical coupling, PMT vs SiPM, etc.

-

Fabrication Technology #4: Laser + diamond drilling

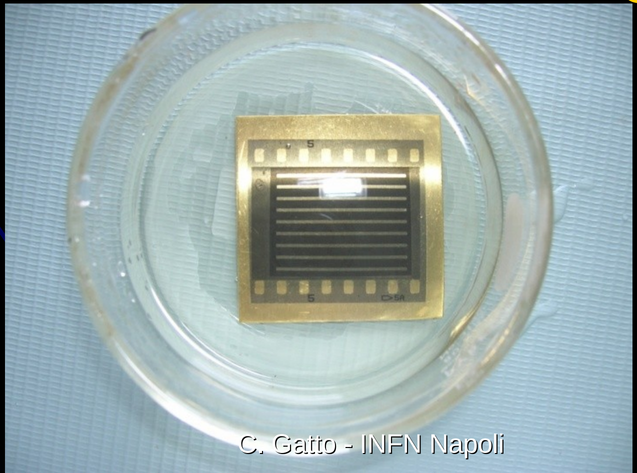




Nd-YAG laser

Fabrication Technology #5: Photo-etching

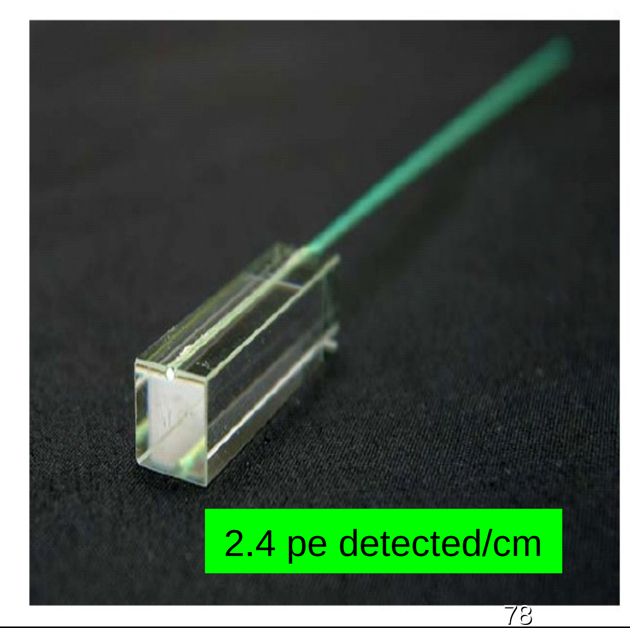
Early stages of R&D



ADRIANO Simulations in ILCroot

- **ILCroot: C++ Software architecture based on root, VMC & Aliroot**
  G3, G4, Fluka + all ROOT tools (I/O, graphics, PROOF, data structure, etc)
  - ***Single framework, for generation, simulation reconstruction and analysis***
- *ADRIANO* is a melting pot of <u>well established</u> experimental methodologies
- All algorithms are implemented parametrically
- Use known experimental setups to normalize the overall results:
  - ***DREAM* for scintillating light production (fiber calorimeter is OK, BGO+fibers not quite there)**
  - ***CHORUS* for instrumental effects with sci-fibers**
  - ***R. Dollan Thesis* for WLS light collection with SF57**

Instrumental effects included in ILCroot:
- SiPM with ENF=1.016
- Fiber non-uniformity response = 0.6% (scaled from CHORUS)
- Threashold = 3 pe (SiPM dark current < 50 kHz)
- ADC with 14 bits
- Constant 1 pe noise.



Next: New Glasses R&D in T1015

- **Research mostly carried at Department of Materials and Environmental Engineering at Uni-Modena (Italy)**
- Heavy glasses with ***no-Pb*** (Cerenkov only)
  - ***Mostly Bi based (heavier, less environmental issues, higher n_D, lower softening point for molding)***
  - ***WO_2 under study (just purchased a 1600 °C furnace)***
  - ***Goal is >8 gr/cm^3***
- Rare earths doped scintillating heavy glasses:
  - ***Ba-Bi-B matrix to accomodate Ce_2O_3 :***
  - ***Density achieved up to now: 7.5 gr/cm^3 (see next slide)***
  - ***Several rare earth oxides tested: Dy_2O_3 promising***
  - ***Lithium content for neutron sensitivity***
- Organic scintillator doped heavy glasses:
  - ***Requires low melting point glass matrix (< 500 °C)***
  - ***Currently under R&D at DIMA: P-T-F-P glass (up to 5.8 gr/cm^3)***

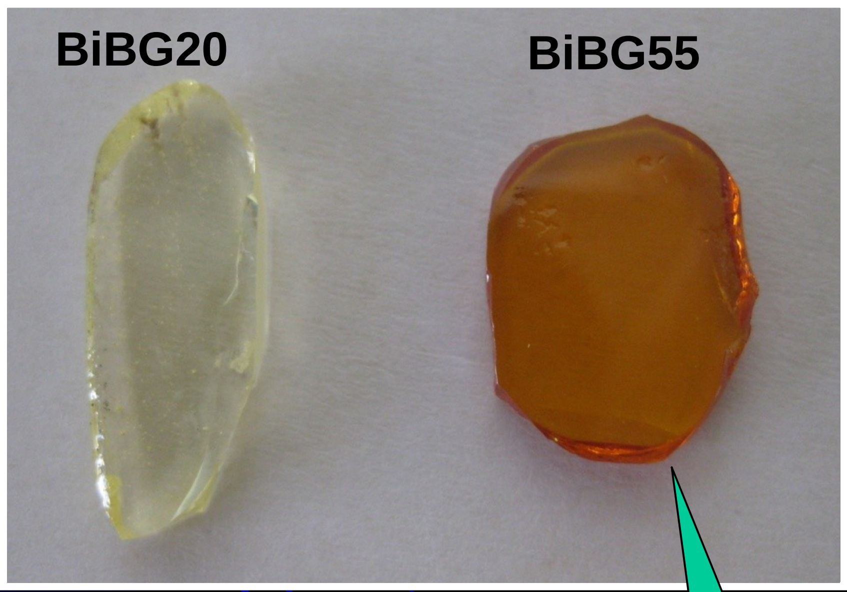
See D. Groom talk at CALOR2012

Consuelo Mugoni

Bismuth Borate Glasses BiB-G

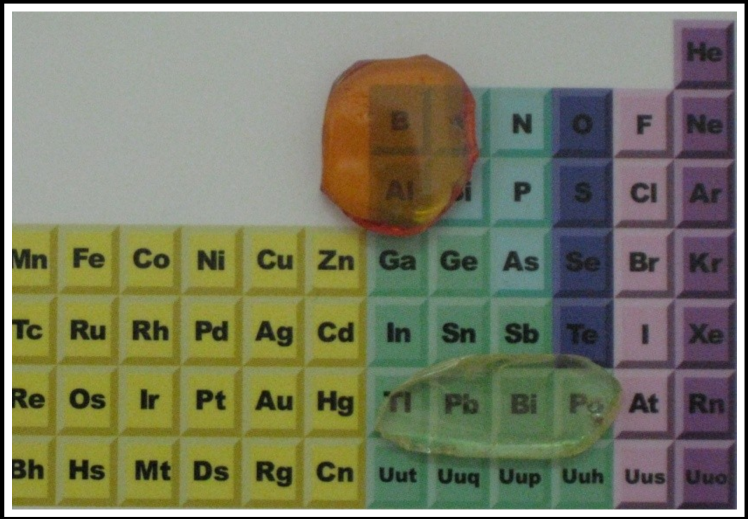
Goal *High density glasses by melt quench method*

- ***Two compositions (BiBG20 and BiBG55) with different Bi_2O_3 content***



Bi_2O_3 mol%

Dark color due to Bi_2O_3 not pure enough



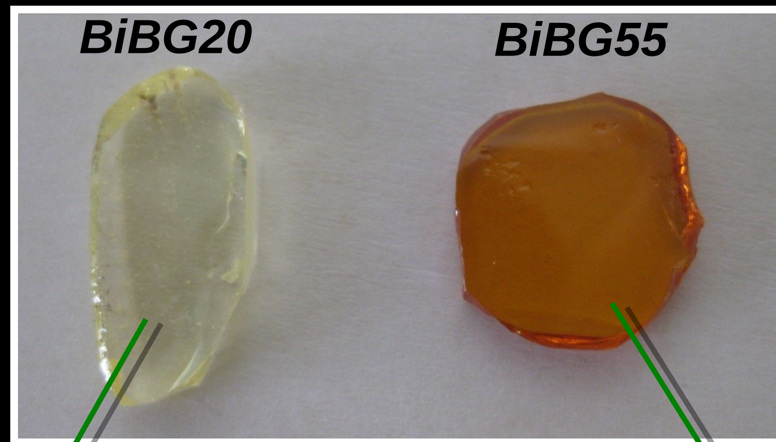
DENSITY

Glass	ρ (g/cm³)
BiBG 20	4.57
BiBG 55	7.48

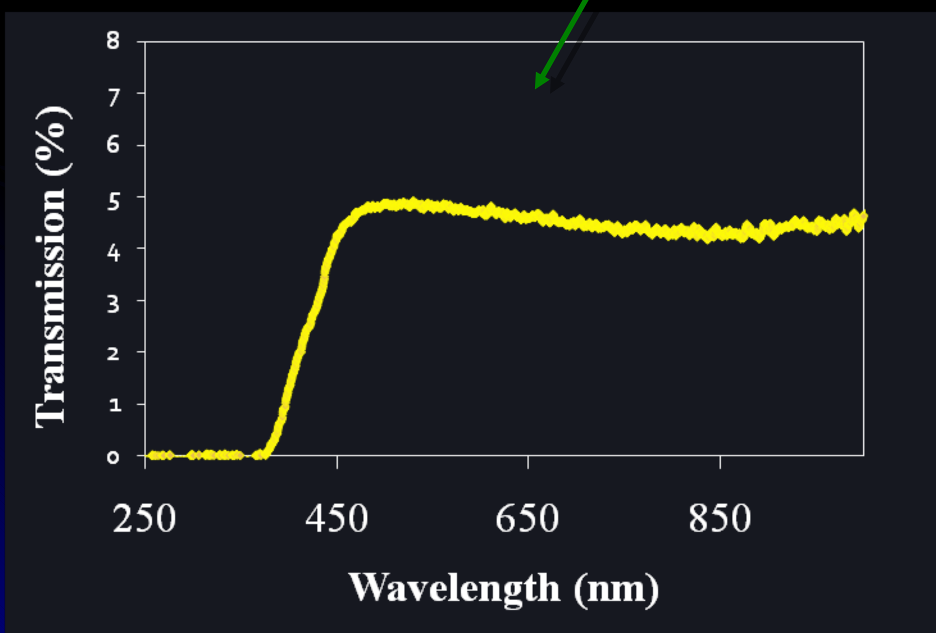
exp.error ± 0.01

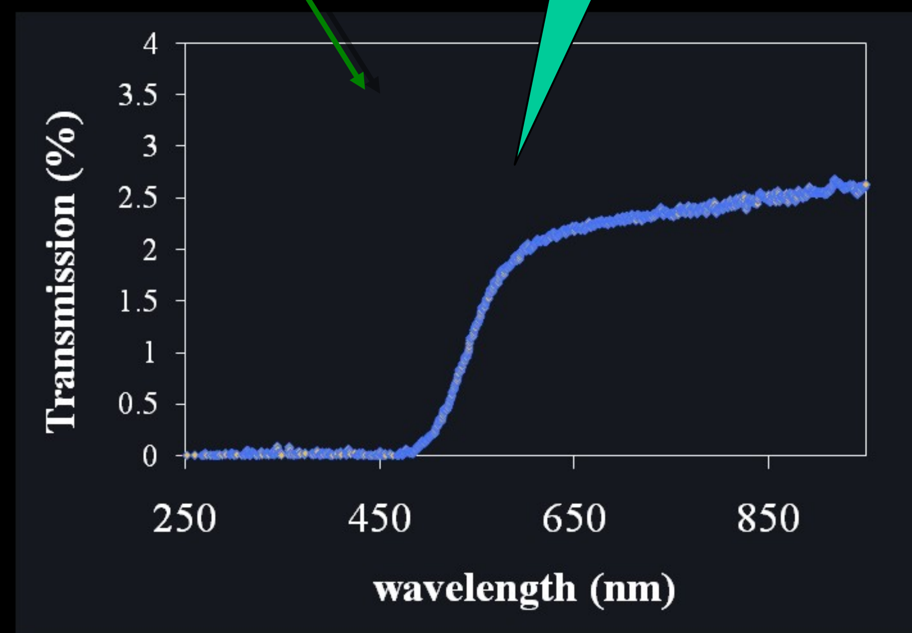
Consuelo Mugoni

Transmission Spectra



No absorption bands





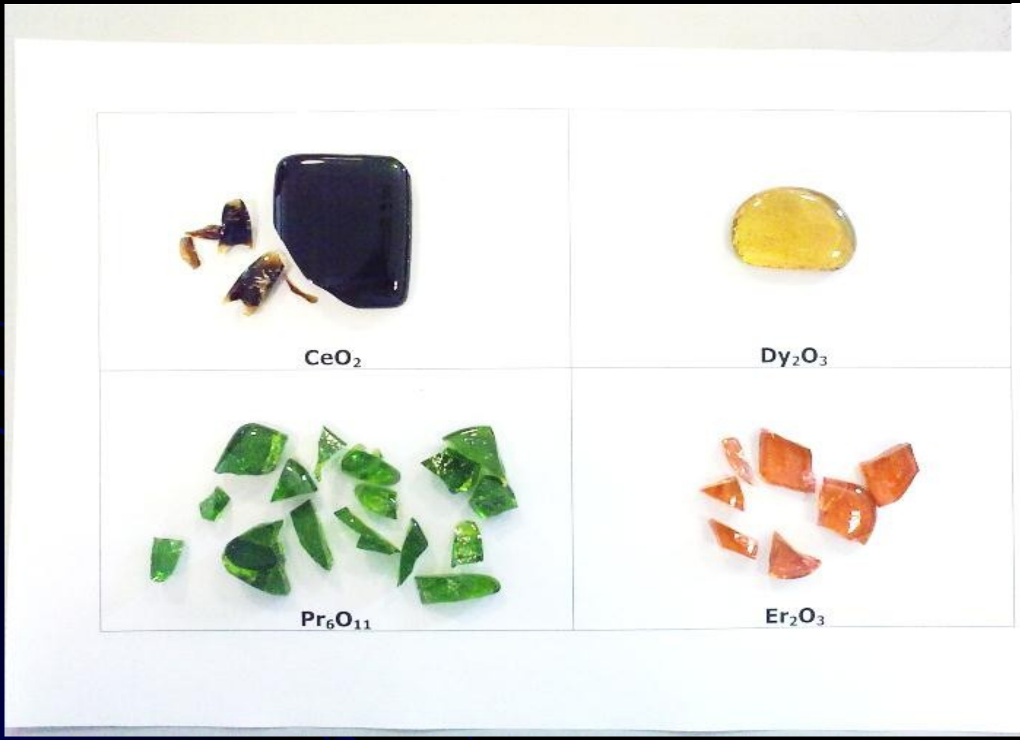
thickness c.a 0.3 cm

thickness c.a 0.3 cm

Consuelo Mugoni

Rare Earth Heavy Glasses

- Rare earths oxides + Ho_2O_3 + ZnO + P_2O_5+B_2O_3+SiO_2
- R.e. considered: CeO_2, Dy_2O_3, Nd_2O_3, Pr_6O_{11}, Er_2O_3

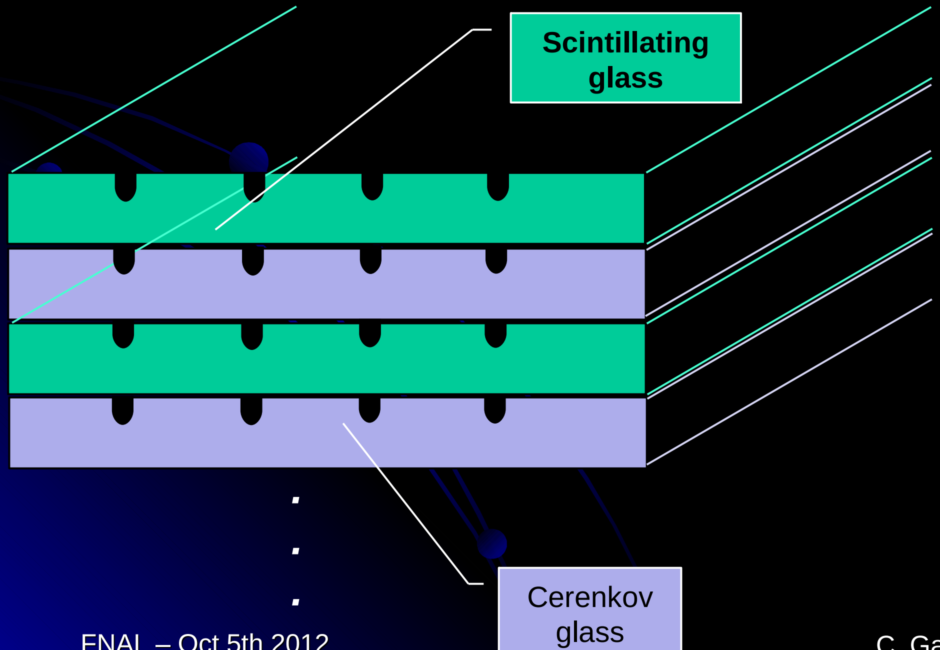


Composition	Density (g/cm^3)
CeO_2	3,3776
Pr_6O_{11}	3,7445
Dy_2O_3	3,8851
Er_2O_3	4,0690
Nd_2O_3	4,2441

Department of Materials and Environmental Engineering

ADRIANO II: aka Glass-only ADRIANO

- Advantages:
  - ***No density dilution from scifi plastic***
  - ***Excellent EM calorimeter***
  - ***Easier to build***
  - ***Cheaper (scifi are expensive!)***
  - ***Requires Li or H in the glass (see D. Groom talk at CALOR2012)***



SCG1- tested at FTBF

Light yield: > 600 pe/Gev (FEE saturating)

T1015 Collaboration at FNAL (28 scientists)

Institution

INFN Trieste/Udine and University of Udine
Fermilab
INFN NA
Lecce University
INFN and University
Roma I

University
of Salerno

University
of Modena

Collaborator

Diego Cauz
Anna Driutti
Giovanni Pauletta
Lorenzo Santi
Walter Bonvicini
Aldo Penzo
Erik Ramberg
Paul Rubinov

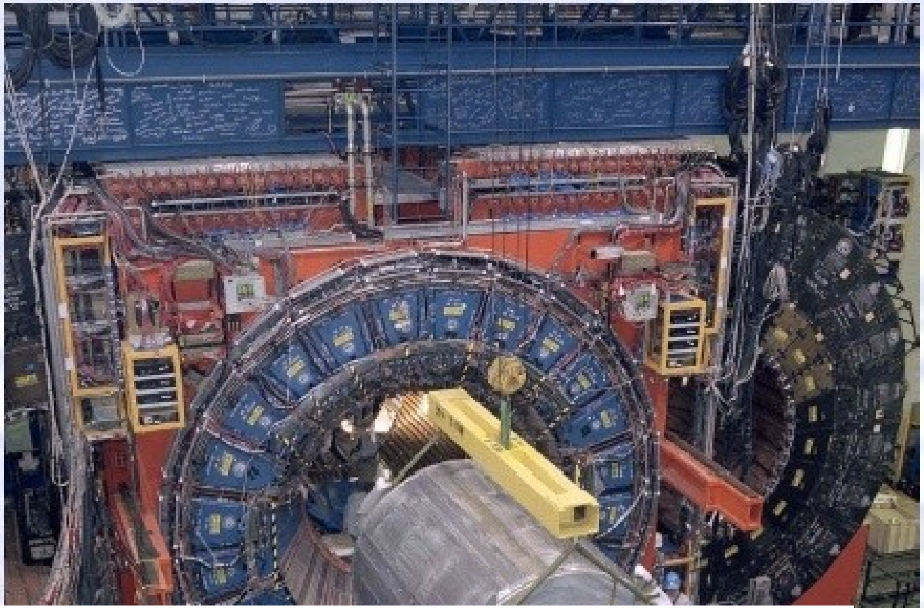
Hans Wenzel
Gene Fisk
Aria Soha
Anna Mazzacane
Benedetto Di Ruzza
Corrado Gatto
Vito di Benedetto
Antonio Licciulli
Massimo Di Giulio
Daniela Manno
Antonio Serra

Maurizio Iori

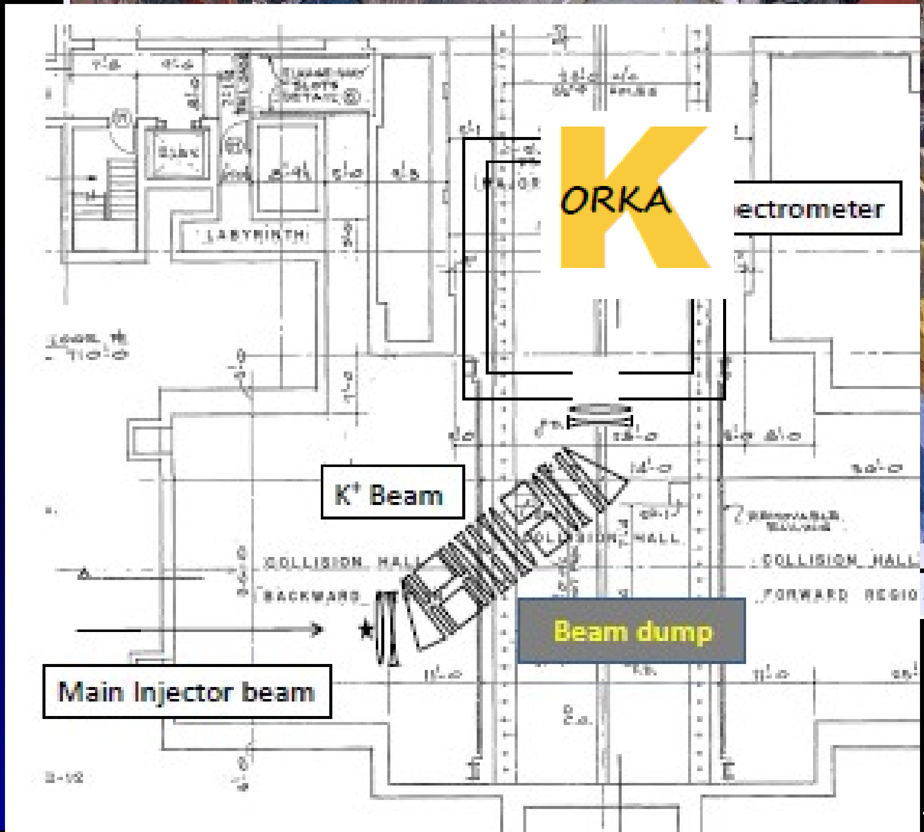
Michele Guida
NEITZERT Heinrich Christoph
SCAGLIONE Antonio
CHIADINI Francesco
Cristina Siligardi
Monia Montorsi
Consuelo Mugoni
Giulia Broglia

Future Prospects & Conclusions

- **Cerenkov ligth yield more than adequate for 30%/sqrt(E) calorimetry. Our goal is to make it even better for EM calorimetry**
- Precision molding is (at present) the preferred construction technique: two molds (37 cm long) under construction (flat and grooved)
- **Year 2013 program:**
  - ***14cm x 14cm x 74cm ADRIANO module (total 18 cells)***
  - ***9.2 cm x 4.6 cm x 37 cm module with scintillanti plates***
  - ***9.2 cm x 4.6 cm x 37 cm S+C module (for ORKA experiment)***
  - ***Test beam of scintillating glass module***
- **Ohara sponsorship/partership for bismuth optical glass (6.6 gr/cm^3, n_d = 2.0) in progress: two strips (total 1.4 Kg) provided at no cost**
- New Ohara heavy glass tested in 2012 at FNAL
  - ***7.54 gr/cm^3 ; n_d = 2.24***
- *ADRIANO*2 (Cerenkov + scintillating glass)
- **Heading toward a large prototype**
  - ***1,800 PMT appropriated from CDF***
  - ***2 ton SF57 left from NA62 calorimeter construction***

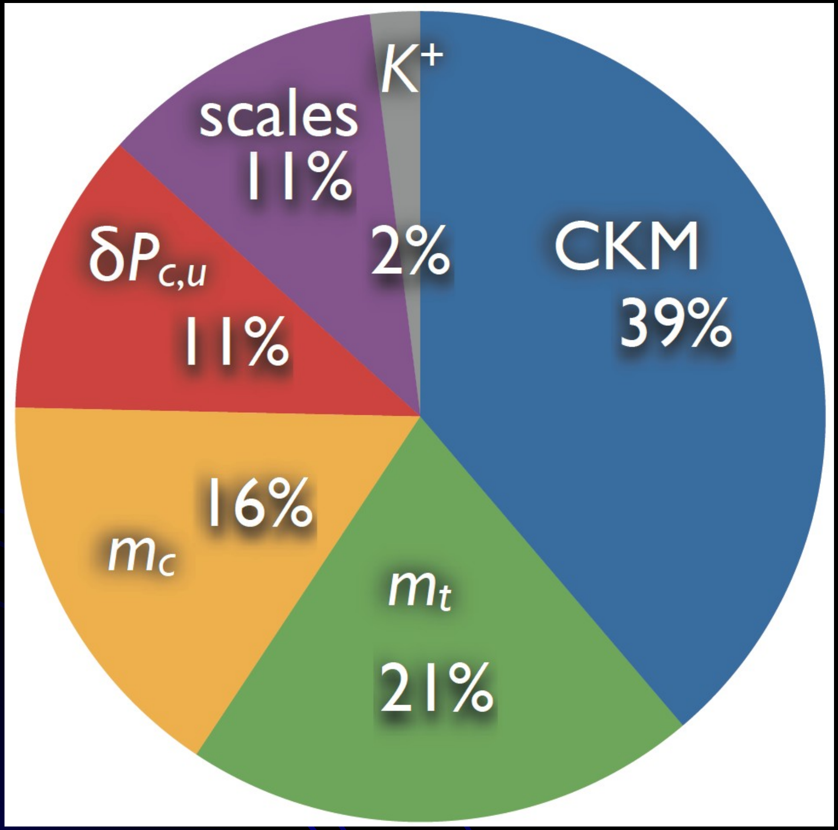


The ORKA new detector payload replaces the CDF tracker volume.



Summary of SM Theory Uncertainties

CKM parameter uncertainties dominate the error budget today.



With foreseeable improvements, expect total SM theory error ≤6%.

SM accuracy of <5%, motivates 1000-event experiments

(ORKA proposal)

Unmatched by any other FCNC process (K or B).

30% deviation from the SM would be a 5σ signal of NP

Ex.:

$$M_{\rm NP} = \frac{4\pi}{\Lambda^2} C \bar{d}_L \gamma_\alpha s_L \bar{\nu} \gamma^\alpha \nu,$$

For Re(*C*)~Im(*C*)~*O*(1), a 10% measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ or $K_L \to \pi^0 \nu \bar{\nu}$ would probe $\Lambda \sim O(3{,}000\ \mathrm{TeV})$

SM theory error for $K_L^0 \to \pi^0 \nu \bar{\nu}$ mode exceeds that for $K^+ \to \pi^+ \nu \bar{\nu}$.

J. Brod, M. Gorbahn, and E. Stamou, Phys. Rev. D83, 034030 (2011) [arXiv:1009.0947 [hep- ph]].

$K^+ \to \pi^+ \nu\bar{\nu}$ Prospects

Now: $\mathrm{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x 10^{-10}$

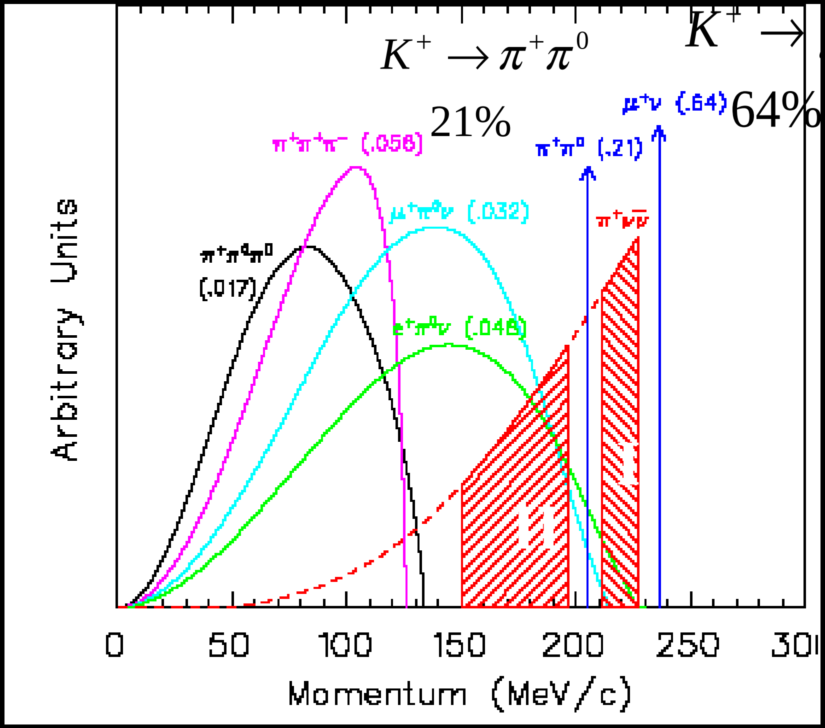
(7 events)

Future: Sensitivity at SM $0.78x10^{-10}$

Goals	NA62 CERN	ORKA	ORKA at Proj. X
Events/ yr	50	210	340
S/N	5	5	5
Precision	10%	5%	2%

Special Features of Measuring

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$



Experimentally weak signature with background processes exceeding signal by $>10^{10}$

Determine everything possible about the K^+ and π^+

* π^+/μ^+ particle ID better than 10^6 (π^+ - μ^+ - e^+)

Eliminate events with extra charged particles or ***photons***

* π^0 inefficiency $< 10^{-6}$

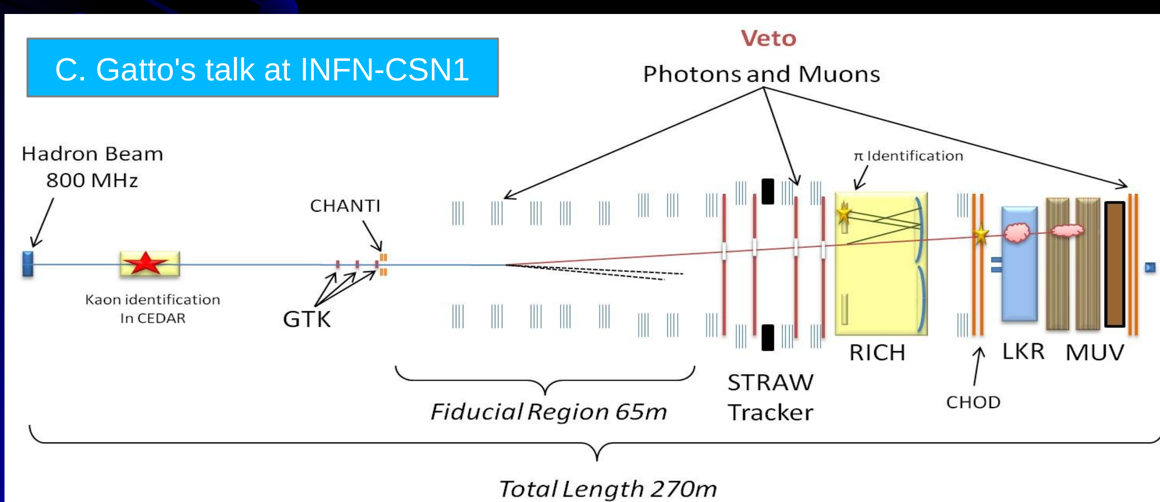
Suppress backgrounds well below the expected signal (S/N~10)

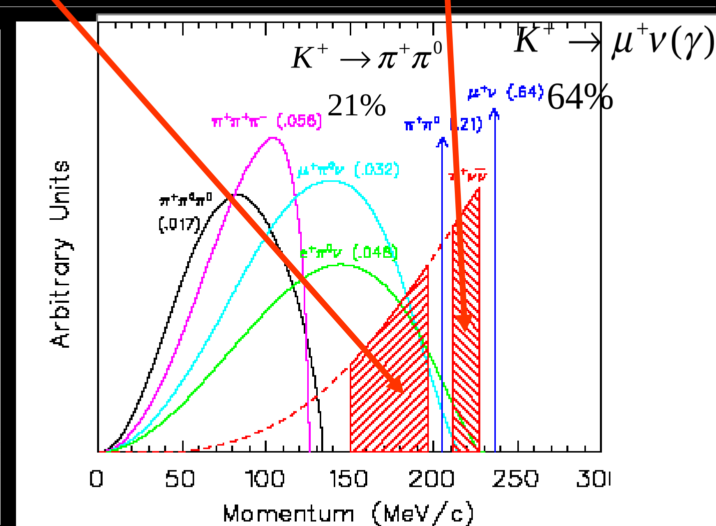
* Predict backgrounds *from data*: dual independent cuts
* Use "Blind analysis" techniques
* Test predictions with outside-the-signal-region measurements

Evaluate candidate events with S/N function

NA62 vs ORKA

	NA62	ORKA
Technique	In-flight decay	Stopped K
Beam	Unseparated p/K (60% K)	Pure K
Phase space targeted	Lower region	Higher region
E/p detected	O(10 GeV)	1-230 MeV
Critical issues	PID up to 35 GeV ($1-\varepsilon \sim 10^{-5}$)	Accidentals in PV
Advantages	No tagging of $\pi \to \mu \to e$ chain (higher rate)	High precision P measure
Notes	Running must be coincident with LHC, splits run-time with CNGS.	Splits run-time with NOVA.
First results	2017	2020
Sensitivity goal	~80 events	~1000 events





Dual Readout Calorimetry

i.e.: two distinct calorimeters sharing the same absorber

$$E_S=\left[fem+\frac{(1-fem)}{\eta_S}\right]\cdot E_{HCAL}$$

$$E_C=\left[fem+\frac{(1-fem)}{\eta_C}\right]\cdot E_{HCAL} \qquad \left(\eta_S=\left(\frac{e}{h}\right)_s \quad ; \quad \eta_C=\left(\frac{e}{h}\right)_C\right)$$

fem is:

1) Energy dependent -> the calorimeter is non linear
2) Fluctuating event-by-event -> the energy resolution is non gaussian if $\eta_s \surd\neq \eta_c$

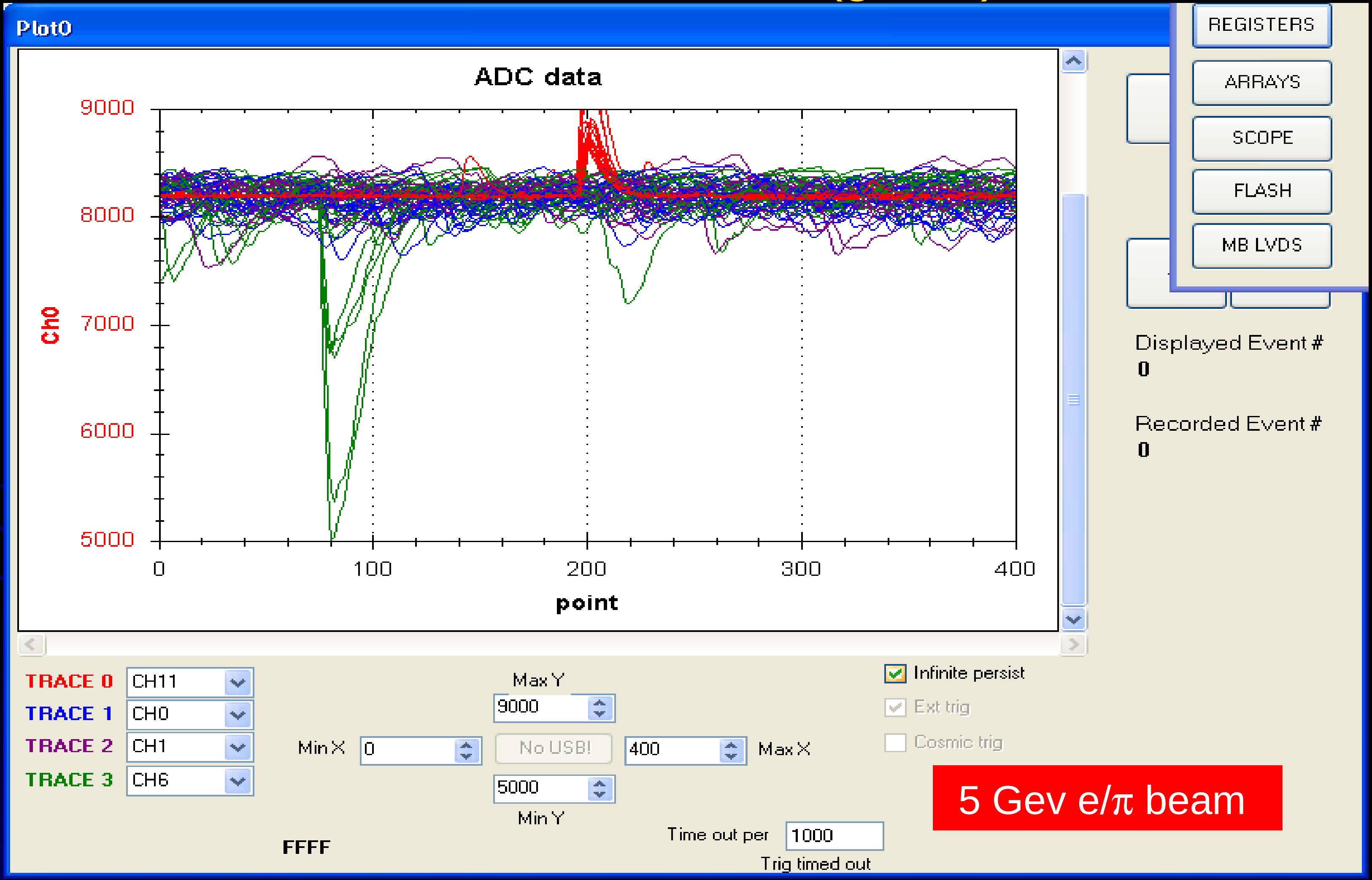
If $\eta_s \surd\neq \eta_c$ then the system can be solved for E_{HCAL}

$$E_{HCAL}=\frac{\eta_S\cdot E_S\cdot(\eta_C-1)-\eta_C\cdot E_C\cdot(\eta_S-1)}{\eta_C-\eta_S}$$

We are measuring fem event-by-event

Waveforms from TB4 DAQ:

SiPM with INFN light concentrator (blue) vs direct fiber readout (green)



ORKA Roadmap in Particle Physics

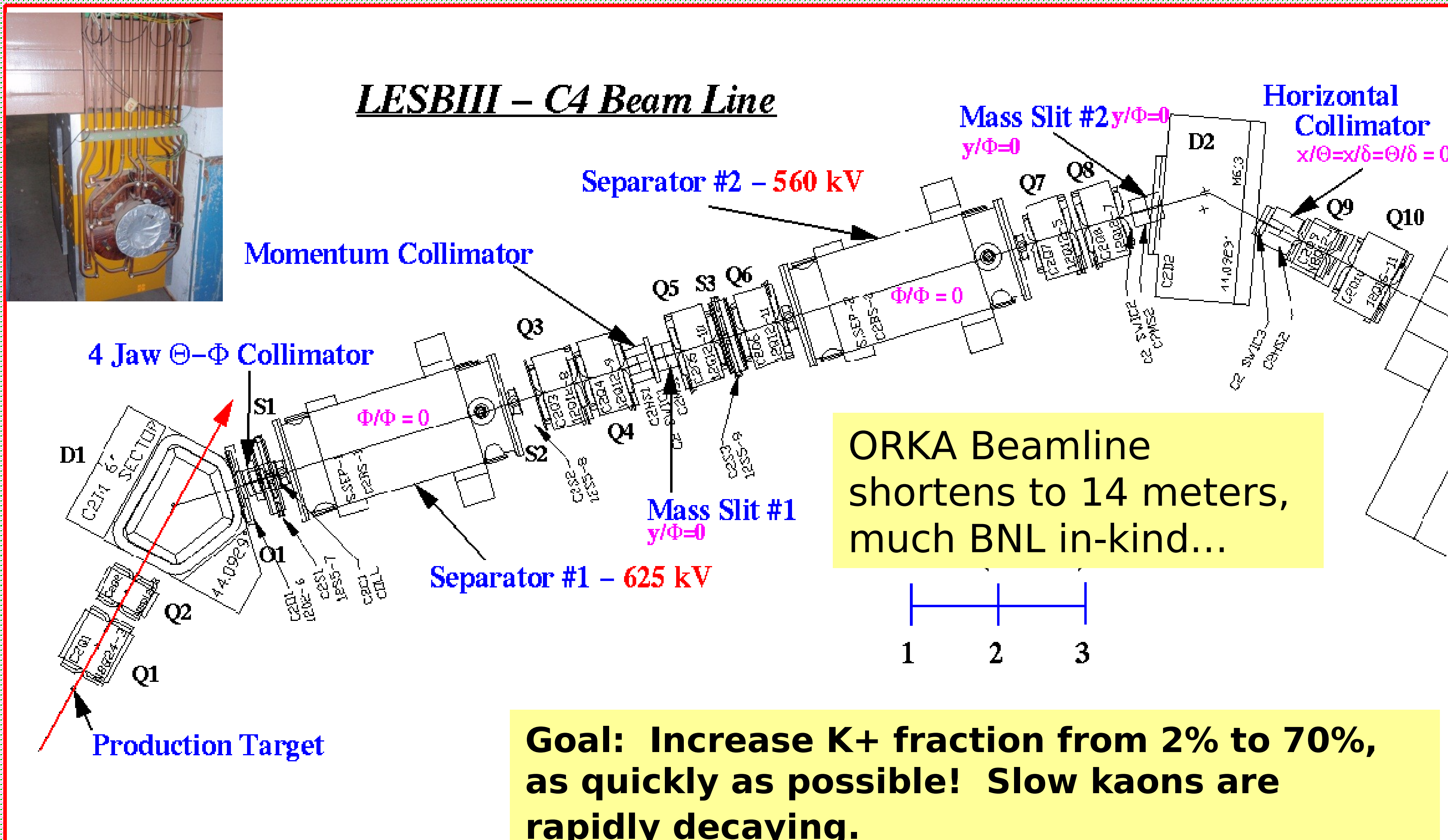
- **2017**, first results from the NA62 CERN experiment:

  - **Evidence of new physics?:** ORKA will embark on confirming with a completely different method, provide definitive measurement.
  - **No evidence of new physics?:** ORKA will push the hunt for new physics to much higher sensitivity.

- **2020,** first results from the ORKA experiment:

  - Evidence of new physics or no evidence of new physics yet: ORKA will continue the hunt to “ultimate” sensitivity. Interplay with results from next generation flavor factories.

separated charged beam on a stopping target.



ORKA Beamline shortens to 14 meters, much BNL in-kind…

Goal: Increase K+ fraction from 2% to 70%, as quickly as possible! Slow kaons are rapidly decaying.

Sensitivity Frontier of Kaon Physics Today

- CERN NA62: 100 x 10^{-12} measurement sensitivity of $K^+ \to e^+\nu$
- Fermilab KTeV: 20 x 10^{-12} measurement sensitivity of $K_L \to \mu\mu ee$
- Fermilab KTeV: 20 x 10^{-12} search sensitivity for $K_L \to \pi\mu e$, $\pi\pi\mu e$
- BNL E949: 20 x 10^{-12} measurement sensitivity of $K^+ \to \pi^+\nu\nu$
- BNL E871: 1 x 10^{-12} measurement sensitivity of